Fermilab

Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

Longitudinal Beam Dynamics Studies at the PIP-II Injector Test Facility

J.-P. Carneiro
on behalf of the PIP-II Injector Test team

Accelerator Physics Seminar, Fermilab

11 October 2018

A little bit of History of the FFC at PIP2IT

- A Fast Faraday Cup (FFC) designed at Fermilab by D. Sun and S. Shemyakin has been in use at the PIP-II Injector Test since 2017 to measure the RMS bunch length of the bunches.

- The FFC samples a small portion of the bunch (3 to 5%).

- For current above 2 mA we observed that, due to space charge effects, the portion of the beam sampled systematically overestimated the RMS bunch length of the full beam.

- Start-to-end simulations of the injector are critically important to properly describe the transverse-to-longitudinal correlation.

- This work will be presented at the CPO-10 conference during a 15 mn talk on 19-Oct-2018.

Outline

- Part I : PIP-II Linac and PIP-II Injector Test Facility
  - Description of the PIP-II Linac
  - Description of the PIP-II Injector Test

- Pat II : Start-to-End model (with TRACEWIN and TRACK) of the PIP-II Injector Test

- Part III: Description of the Fast Faraday Cup

- Part IV: Transverse-to-Longitudinal Correlation (Prediction Vs Observation)

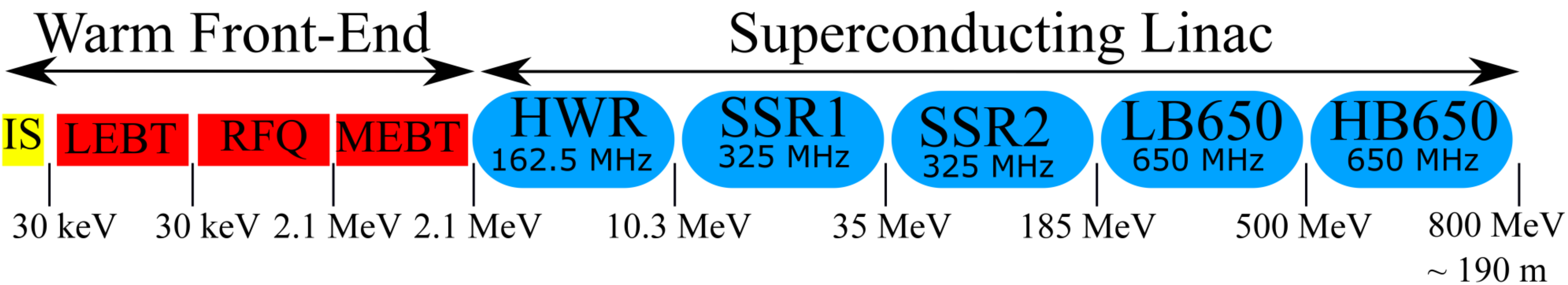
- Part V: Longitudinal emittance estimate at 0.6 mA, 5 mA and 10 mA.

Part I

PIP-II Linac and PIP-II Injector Test

The PIP-II Linac / Layout

- The Proton Improvement Plan II (PIP-II) is an upgrade of the Fermilab accelerator complex with the aim of providing proton beam power of 1.2 MW to LBNF/DUNE.
- The linac is expected to deliver an average H- beam current of 2 mA, at 800 MeV with pulse lengths of 0.55 ms at 20 Hz of repetition rate (1.1 % of duty cycle) for injection into the booster.
- The PIP-II Linac has two major sections: a warm front-end (up to 2.1 MeV) and a superconducting (SC) section.



The PIP-II Linac / Beam Loss Requirement

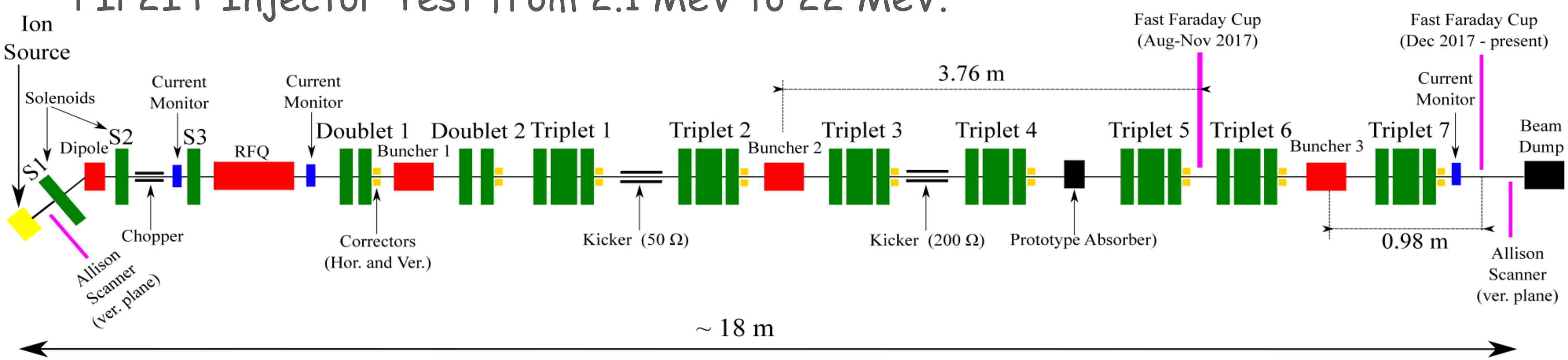
- The linac has been designed with careful control of unexpected beam losses of less 0.1 W/m.
- The principal beam loss mechanism along the linac is expected to be due to the stripping of the H- ions from residual gas, magnetic fields, blackbody radiation and intrabeam scattering.
- Stringent requirements are imposed on beam emittances to ensure the transport of the beam along the linac with marginal losses.

Table: Maximum allowed emittances along the PIP-II Linac at 5 mA. From CDR V0.3, 2018. (1 keV-ns = 0.32 mm-mrad)

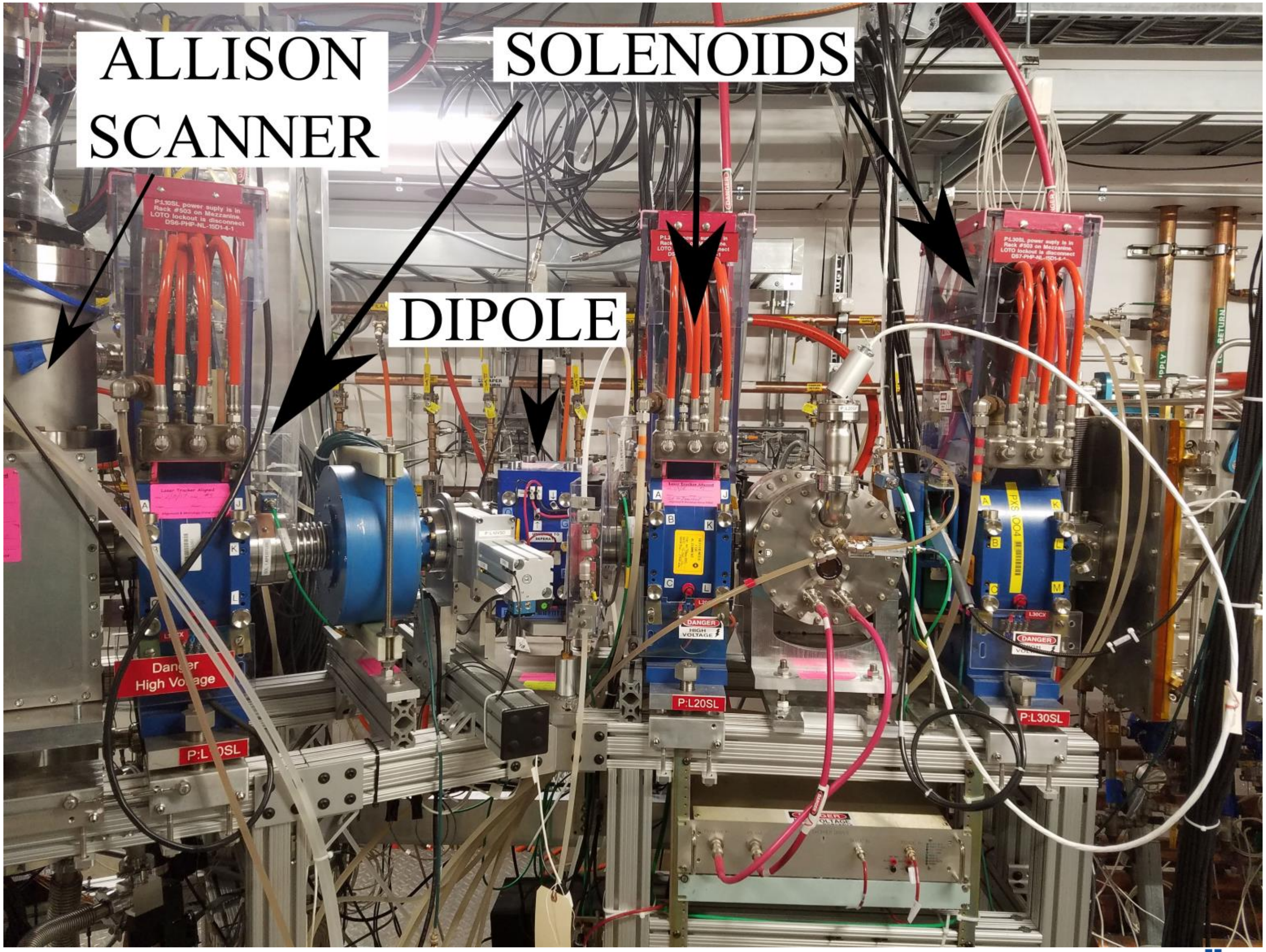
	Transverse Emittance [mm-mrad]	Longitudinal Emittance [mm-mrad]
Ion Source	0.14	-
RFQ Entrance	0.18	-
RFQ Exit	0.20	0.28
MEBT Exit	0.23	0.31
SC Linac Exit	0.30	0.35

The PIP-II Injector Test / Layout

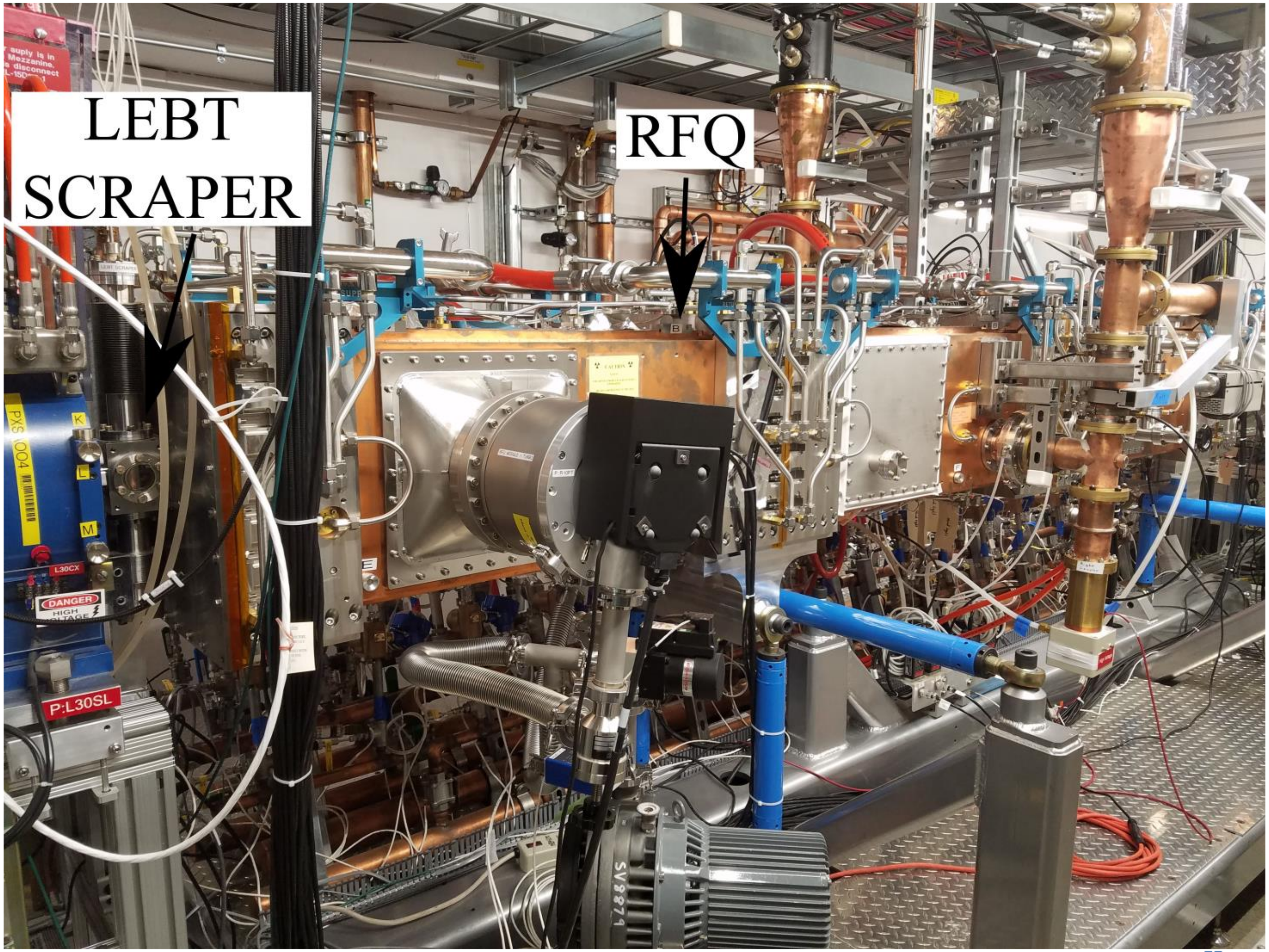
- To alleviate risks associated with the front-end of the PIP-II linac, an Injector Test facility (PIP2IT) is currently under construction at Fermilab.
- In its actual configuration, the PIP2IT comprises an Ion Source, a LEBT, a RFQ and a MEBT. The ion source operates at 30 kV, DC or pulsed with usually long pulses (ms) of 5 mA to 15 mA. A LEBT chopper cut pulses of 0.55 ms at a repetition rate between 1 Hz to 60 Hz with nominal operation at 20 Hz. An additional bunch by bunch selection is performed in the MEBT by two kickers that decreases the average current in the 0.55 ms pulse from 5 mA to 2 mA.
- A Half-Wave Resonator (HWR) cryomodule and the first Single-Spoke Resonators (SSR1) cryomodule will be added in 2019 to boost the beam of the PIP2IT Injector Test from 2.1 MeV to 22 MeV.



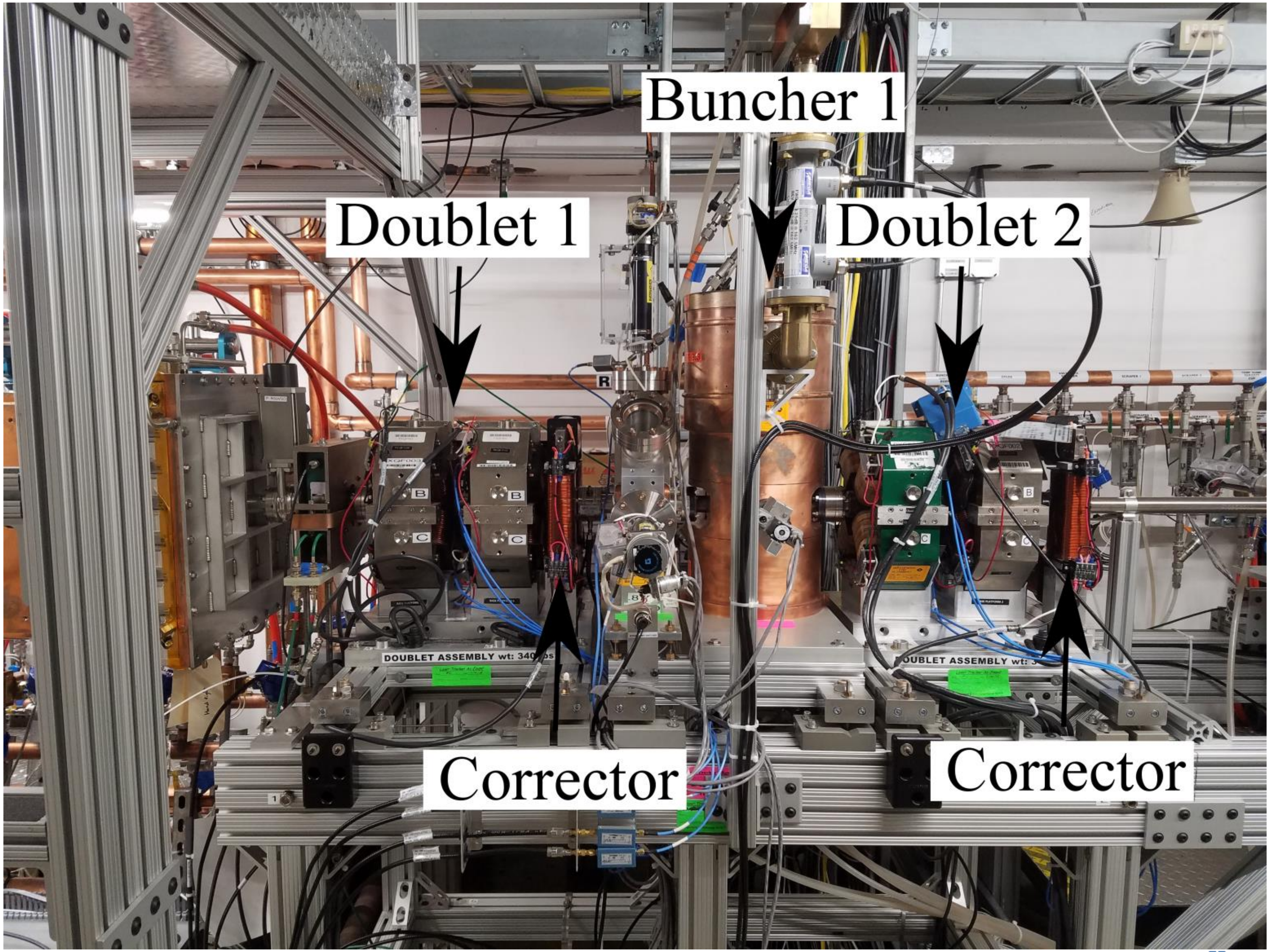
The PIP-II Injector Test / Low Energy Beam Transport



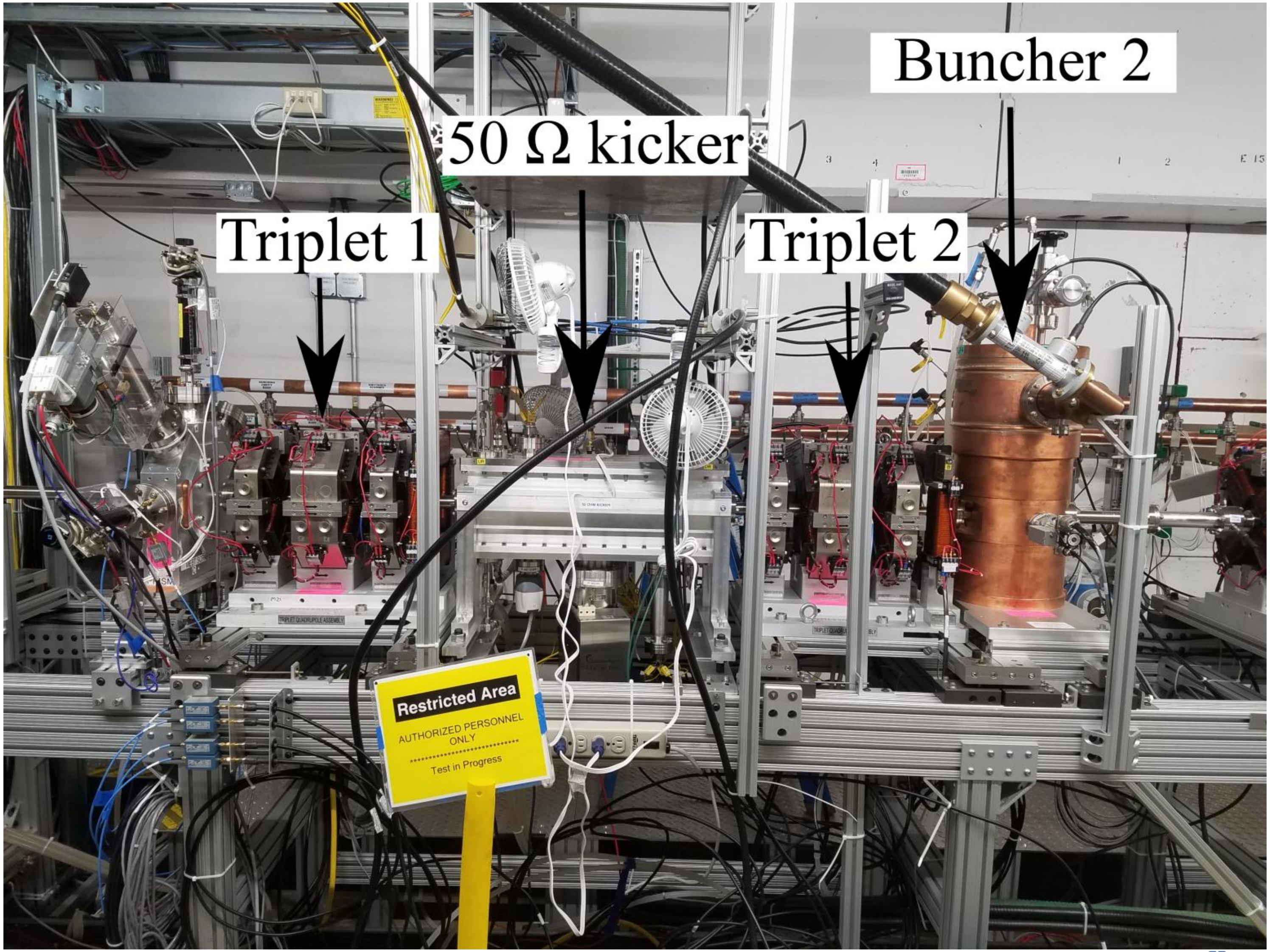
The PIP-II Injector Test / RFQ



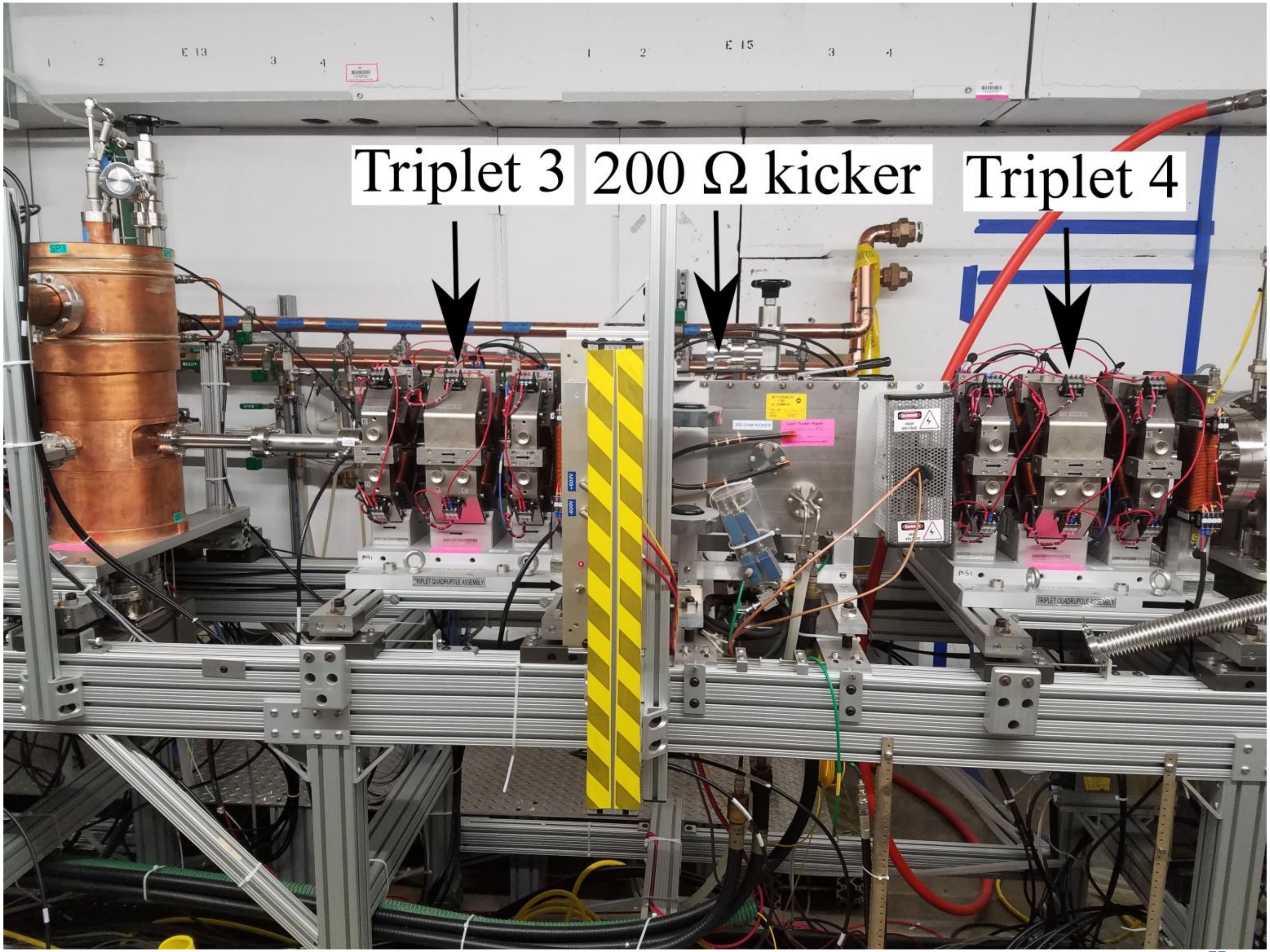
The PIP-II Injector Test / Buncher 1



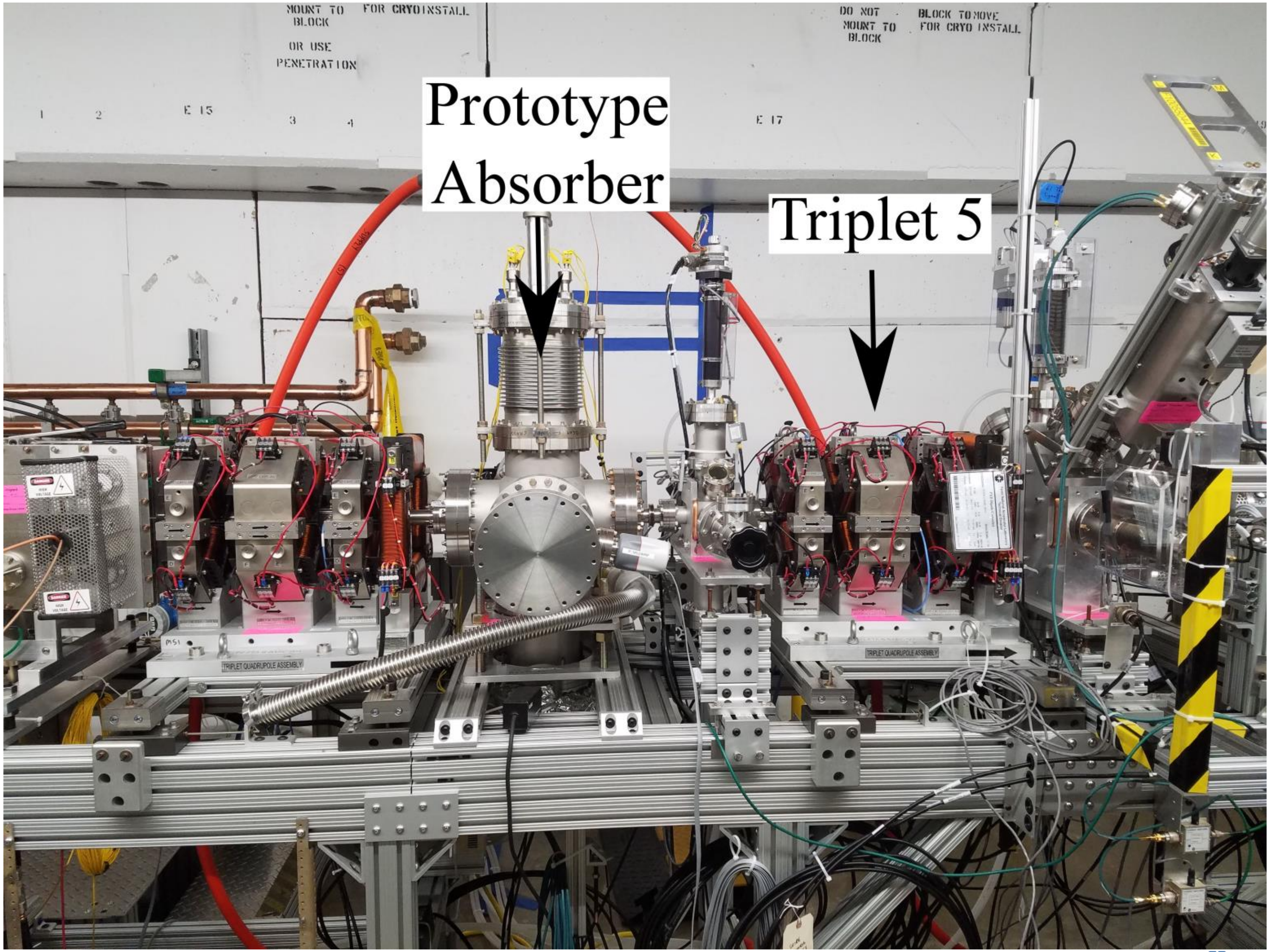
The PIP-II Injector Test / 50Ω kicker



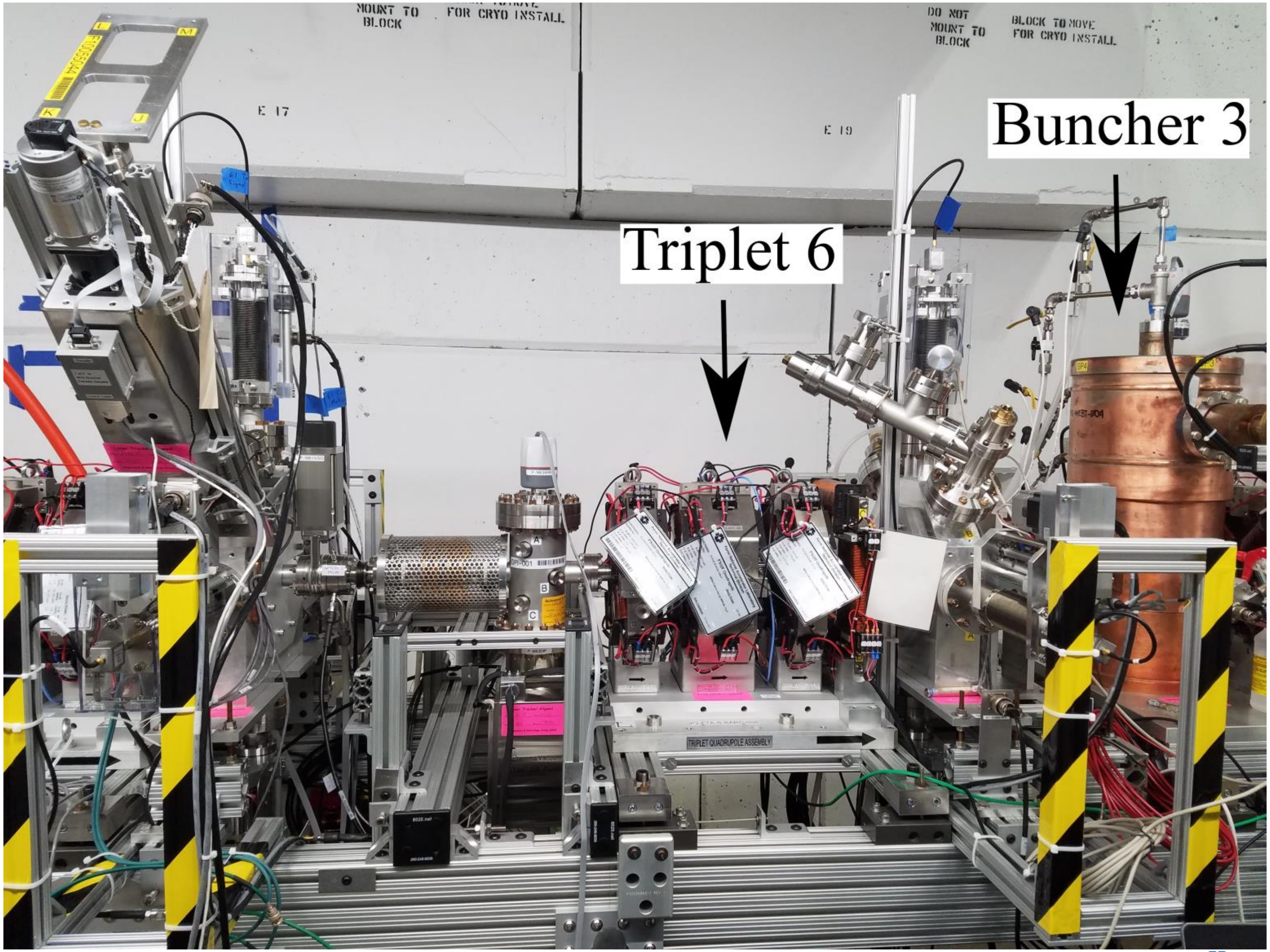
The PIP-II Injector Test / 200Ω kicker



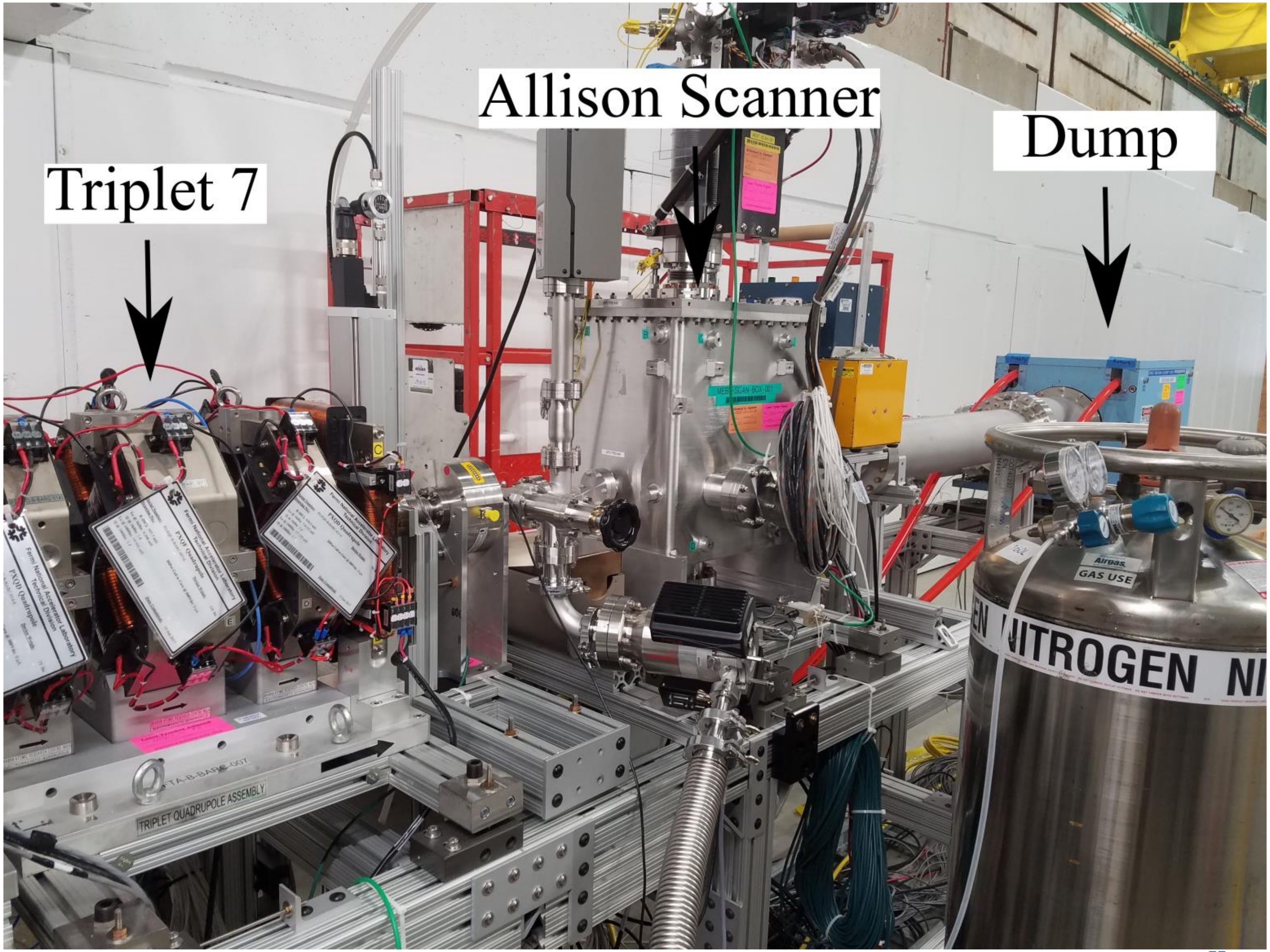
The PIP-II Injector Test / Prototype Absorber



The PIP-II Injector Test / Buncher 3



The PIP-II Injector Test / Dump



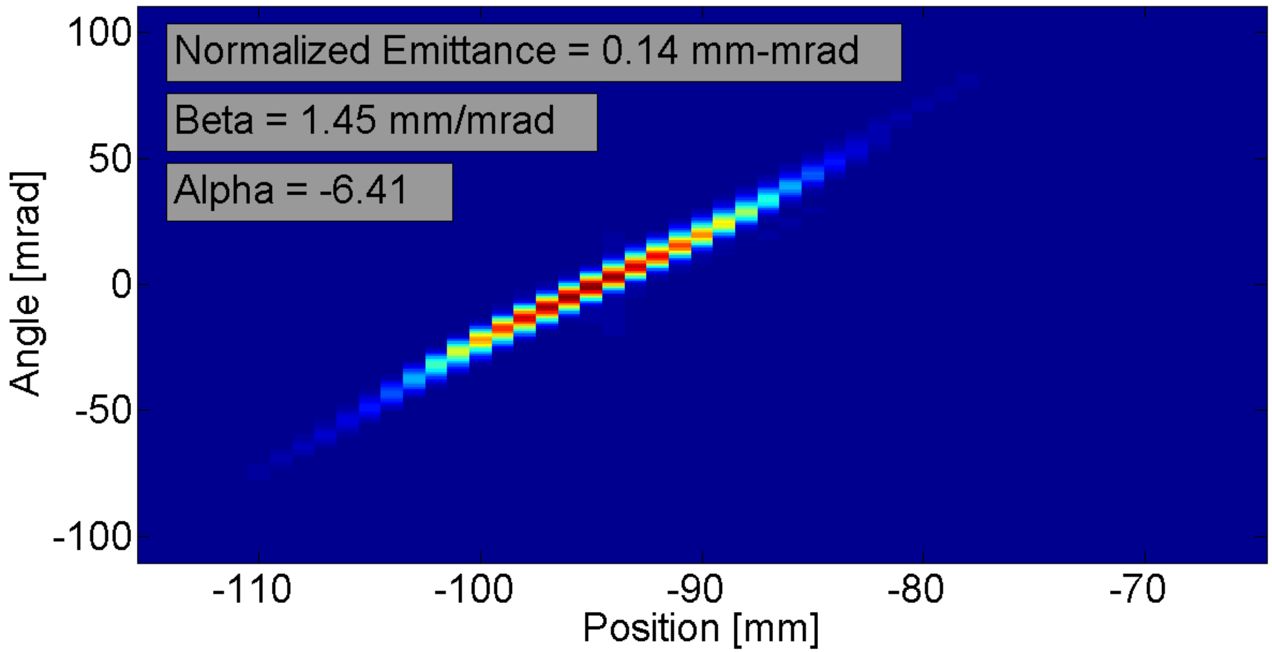
Part II

Start-to-End simulation of the PIP-II Injector Test

The PIP-II Injector Test / Start-to-End Simulation

- A start-to-end model of the PIP2IT linac has been built with the simulation codes TRACEWIN (Saclay, France) and TRACK (ANL)
- The model starts with a 4D Gaussian distribution of 10^6 macro-particles upstream of Solenoid 1 internally built in the codes using measured Twiss parameters from the Allison Scanner distribution at the Ion Source exit.

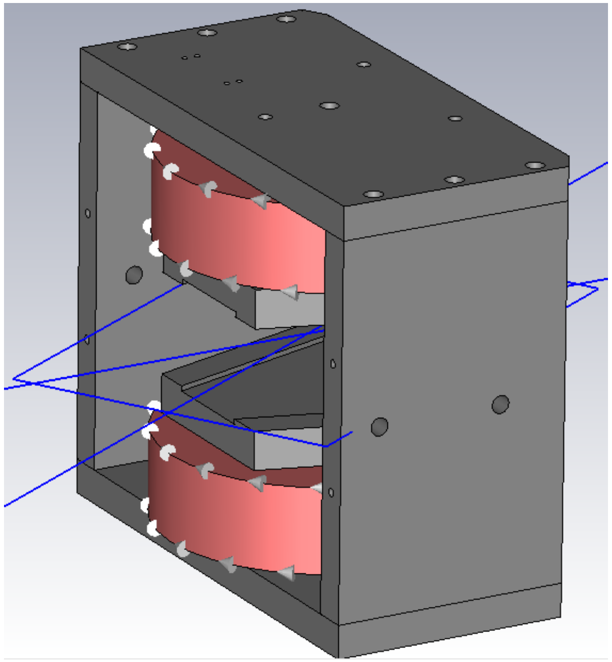
Allison Scanner Image at the Ion Source Exit at 5mA
(C. Richard, MSU/FNAL)



The PIP-II Injector Test / Start-to-End Simulation

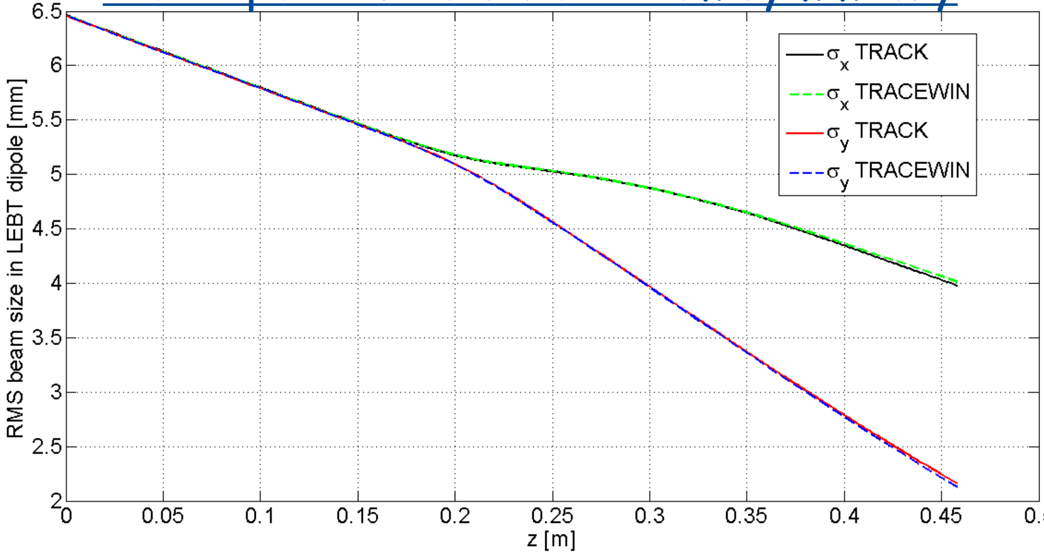
- During typical operation at 5 mA, solenoids current are: S1=138.2A, S2=130A, S3=229A. Space charge effects start 12 cm upstream of the middle of Solenoid 2. Dipole is at 685 G. The RFQ operates at 60 kV.
- The LEBT dipole has been recently implemented in both codes using a 3D grid imported from Micro-Wave Studio (B. Mustapha (ANL), D. Uriot (Saclay))

MWS Model of the LEBT Dipole



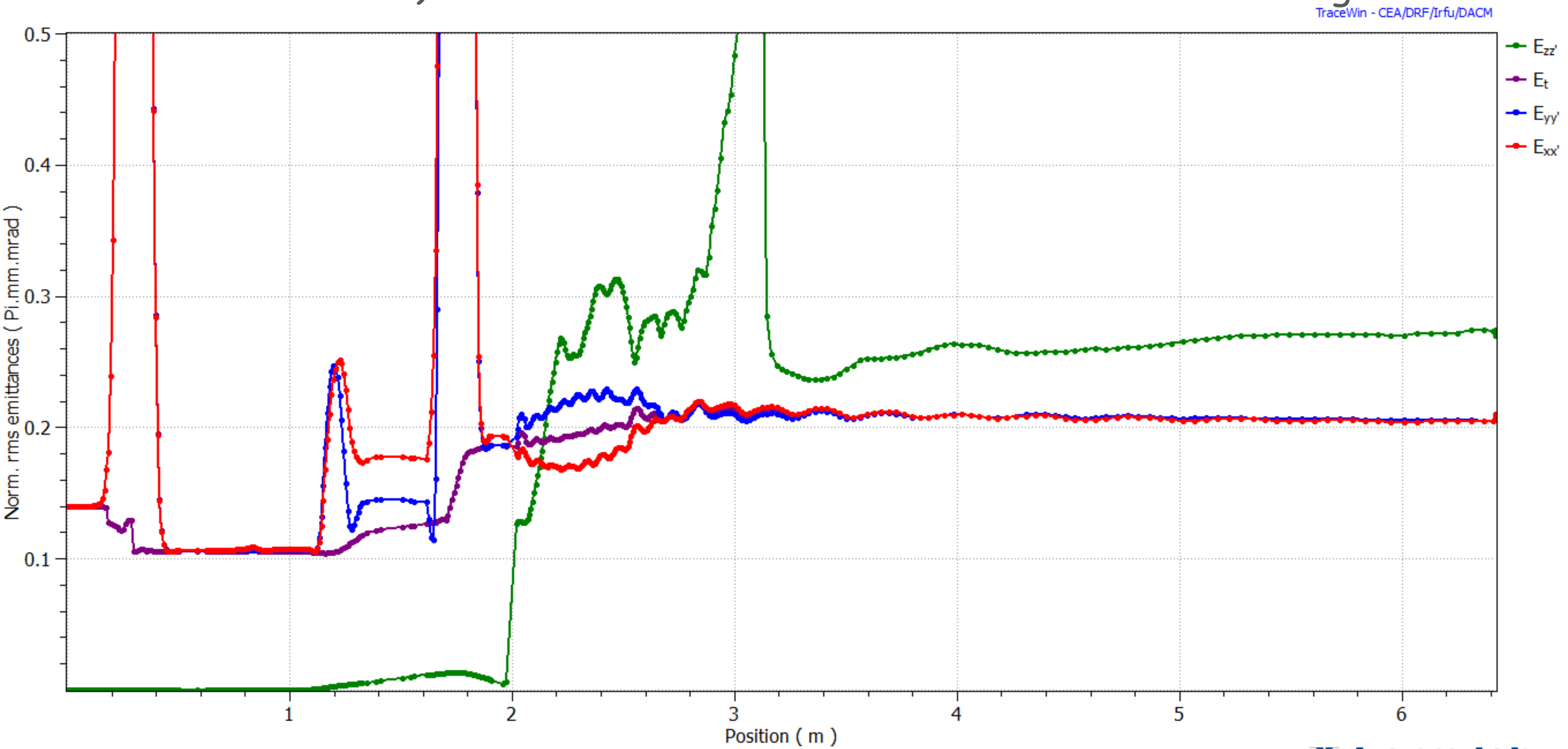
TRACK/TRACEWIN Model of the LEBT Dipole

The dipole breaks the beam symmetry



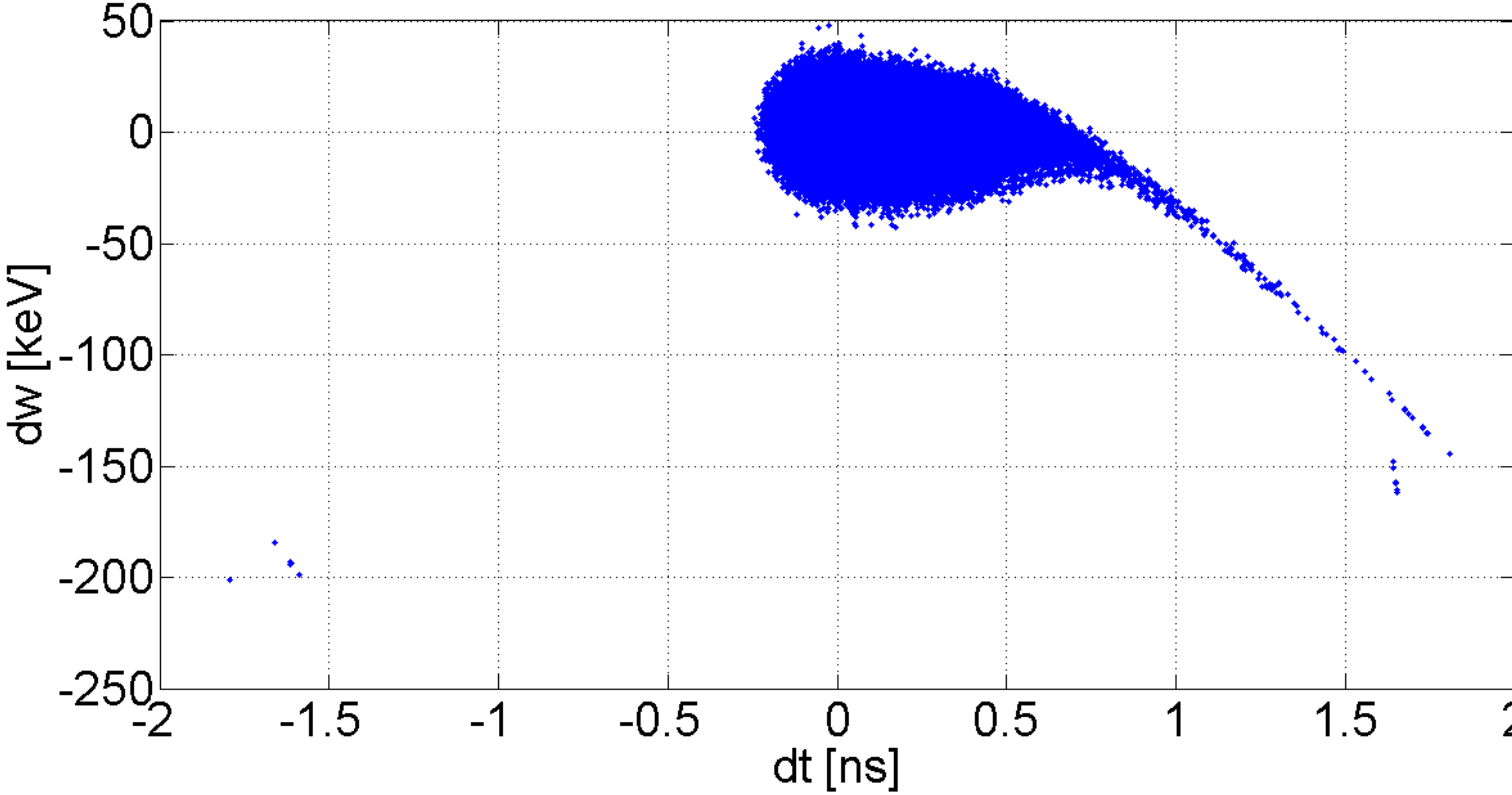
Simulation of PIP2IT / Emittance along LEBT+RFQ
RFQ simulated with Toutatis

- The plot below shows TRACEWIN/TOUTATIS simulation at 5 mA and 10^6 **macro-particles** of the transverse and longitudinal emittance along the LEBT and RFQ including the dipole. TRACEWIN predicts 2% losses in the RFQ (same order as measured). Details of this model need further understanding.



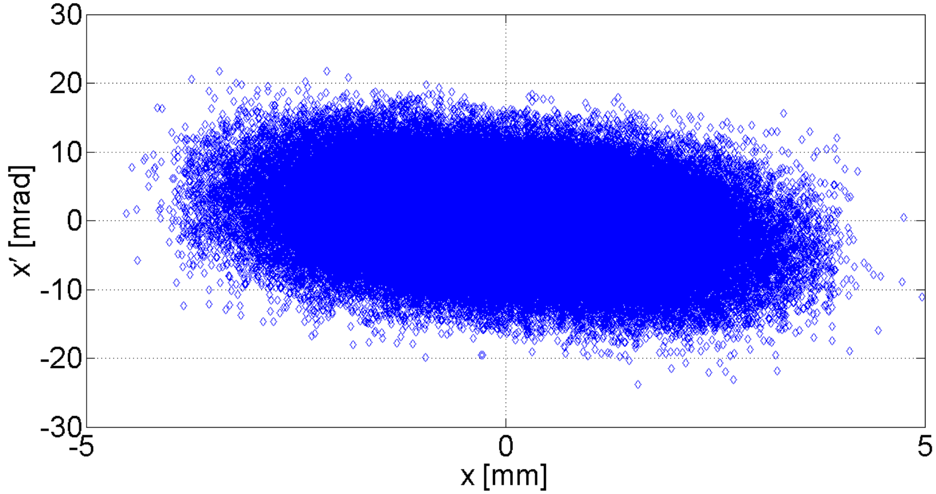
Simulation of PIP2IT / longitudinal Space at RFQ Exit (100%)

- A longitudinal tail/halo containing about 0.1% of the beam is predicted by Tracewin at the RFQ exit.
- Since we are interested by RMS properties we removed the 0.1% of particles with the larger longitudinal action.

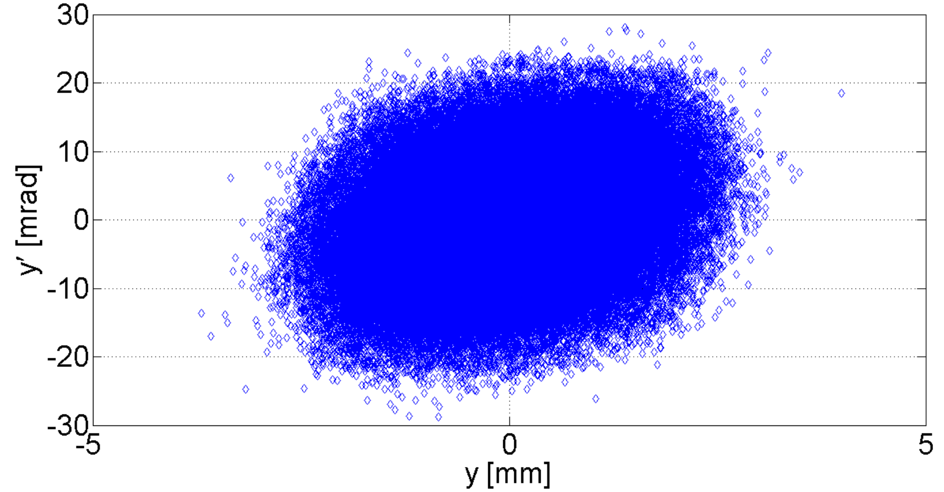


Tracewin / Phase Space at RFQ Exit (99.9%, 729k)
Twiss units: mm/mrad and mm-mrad.($\alpha_z < 0$ *means diverging*)

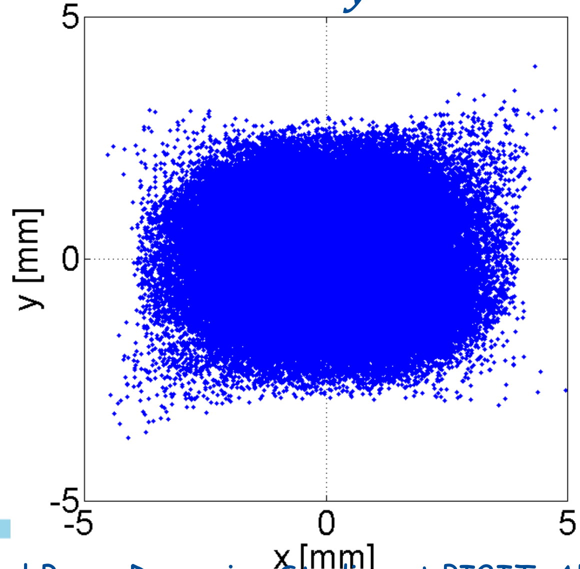
$\alpha_x = 0.31, \beta_x = 0.24\ , \varepsilon_x = 0.21$



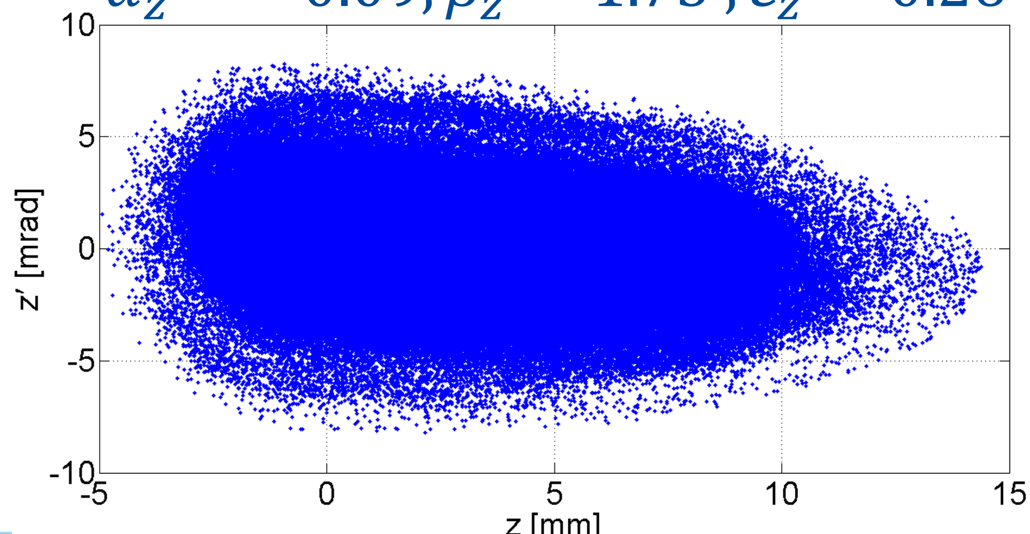
$\alpha_y = -0.22, \beta_y = 0.12\ , \varepsilon_y = 0.21$



$\sigma_x = 0.86\ mm, \sigma_y = 0.62\ mm$

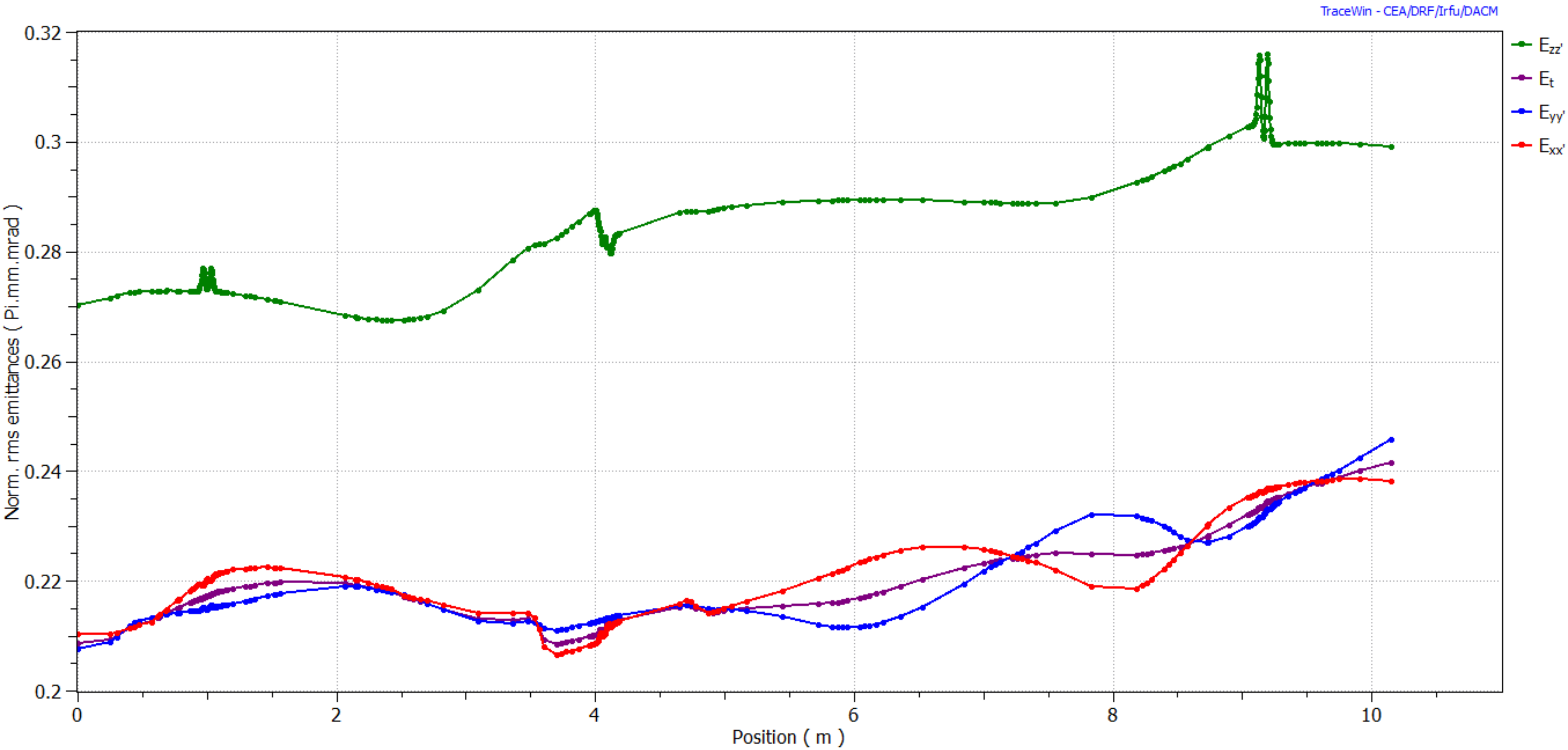


$\alpha_z = -0.09, \beta_z = 1.75\ , \varepsilon_z = 0.26$



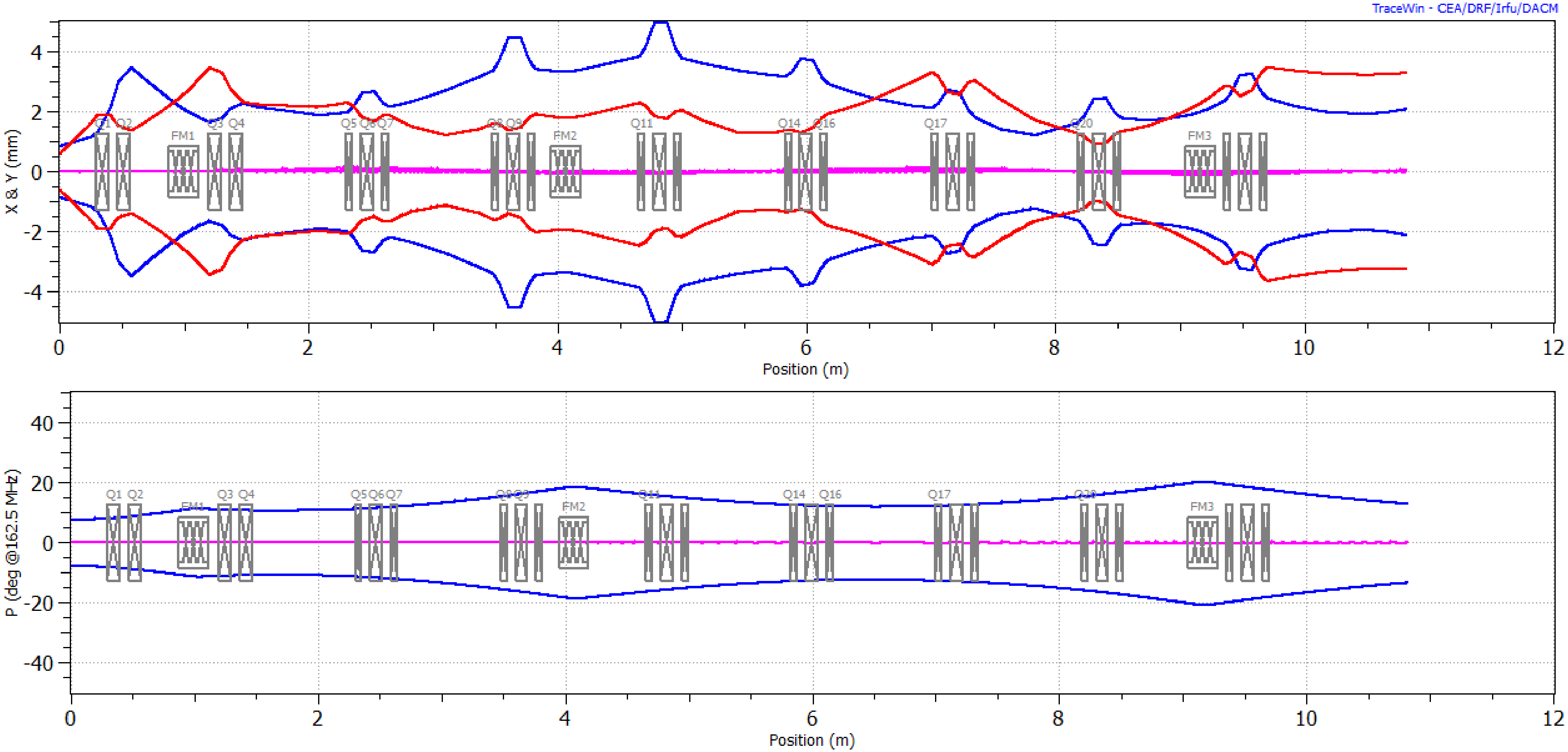
Simulation of PIP2IT with TRACEWIN
Emittance along MEBT

- The plot below shows TRACEWIN transverse and longitudinal emittance evolution at 5 mA along the MEBT for typical 5mA operation lattice.
- Buncher 1 Field set at 60 kV / Buncher 2 and 3 set at 50 kV.



Simulation of PIP2IT with TRACEWIN
RMS Beam Size and Bunch Length along the MEBT

- The plot below shows the corresponding RMS beam size and bunch length at 5mA along the MEBT.
- Typical RMS bunch length vary between 10 to 20 deg (about 170-340 ps)



Part III

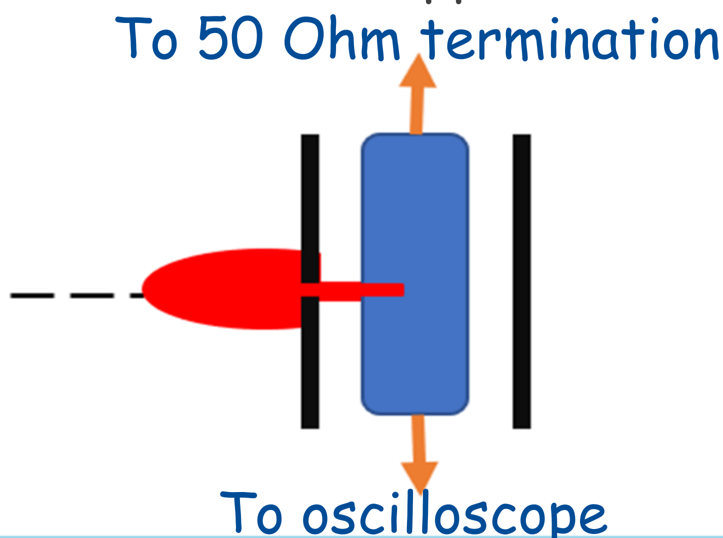
Description of the Fast Faraday Cup

Fast Faraday Cup
Practical realization at PIP2IT

- <u>Complication</u> with measuring the bunch length of a non-relativistic beam with a collector: charges start moving well before bunch arrival

- <u>Solution</u>: cut out a small beamlet and decrease the gap between the ground plate and collector

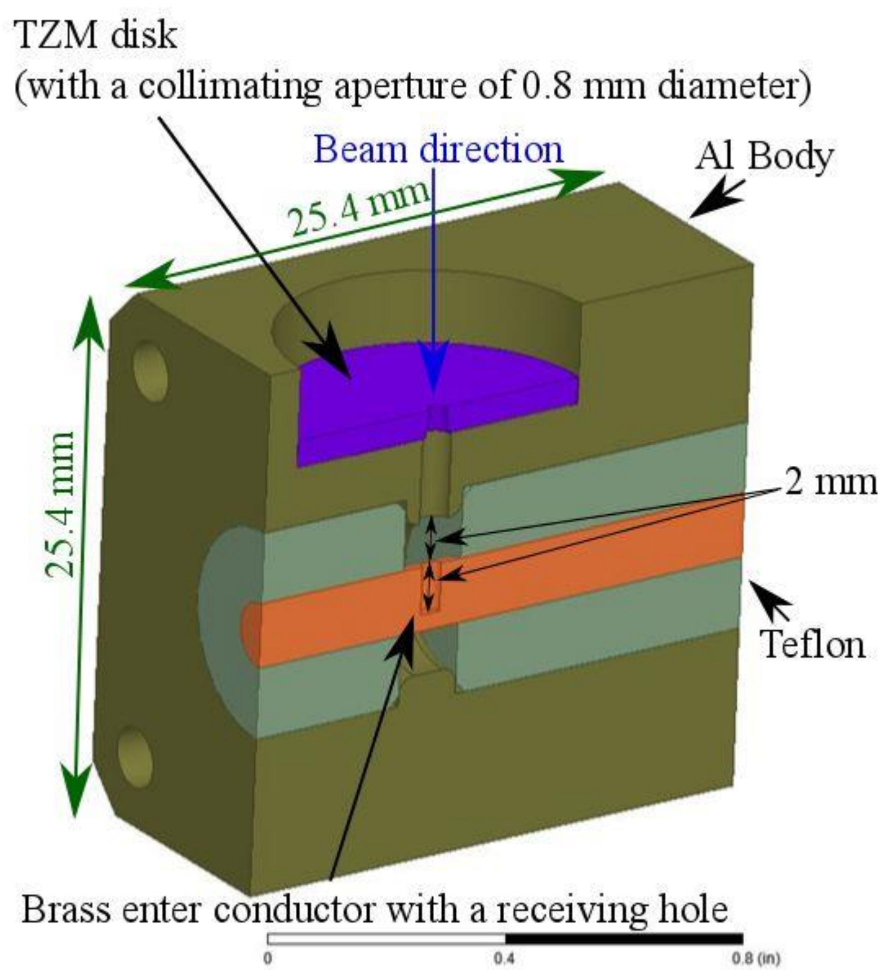
- <u>Important components of the practical realization at PIP2IT</u>
  - Geometry based on a coaxial line provides a high bandwidth
  - A blind hole in the collector suppresses secondary electrons



Fast Faraday Cup / Layout

Patent Pending US 16/101,982. Inventors: Ding Sun, Alexander Shemyakin

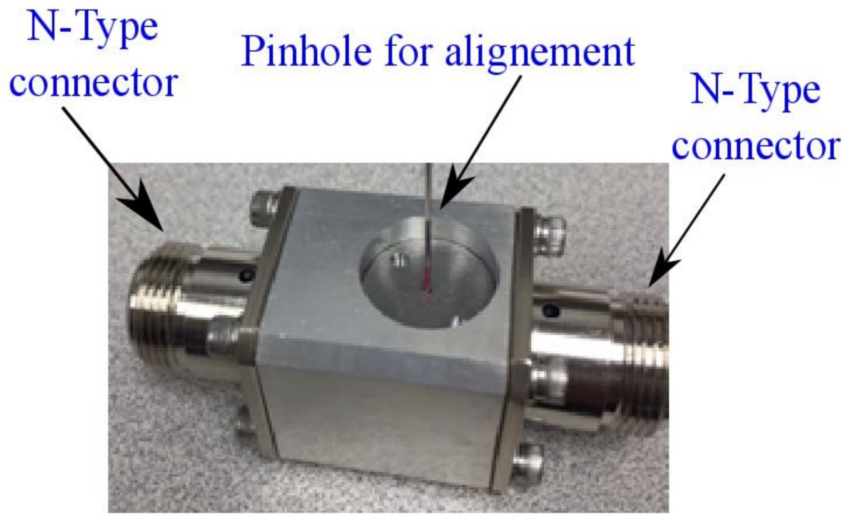
- The FFC head consists of an aluminum body.
- A brass rod serves as a collector and inner electrode
- The beam arrives to a TZM disk with 0.8 mm aperture and travels through a 2 mm gap between the grounded body and the collector.
- The beam is absorbed within a 2 mm deep and 1 mm ID blind hole in the collector.
- The secondary and reflected particles stay mostly inside the collector because the hole depth (twice larger than diameter)



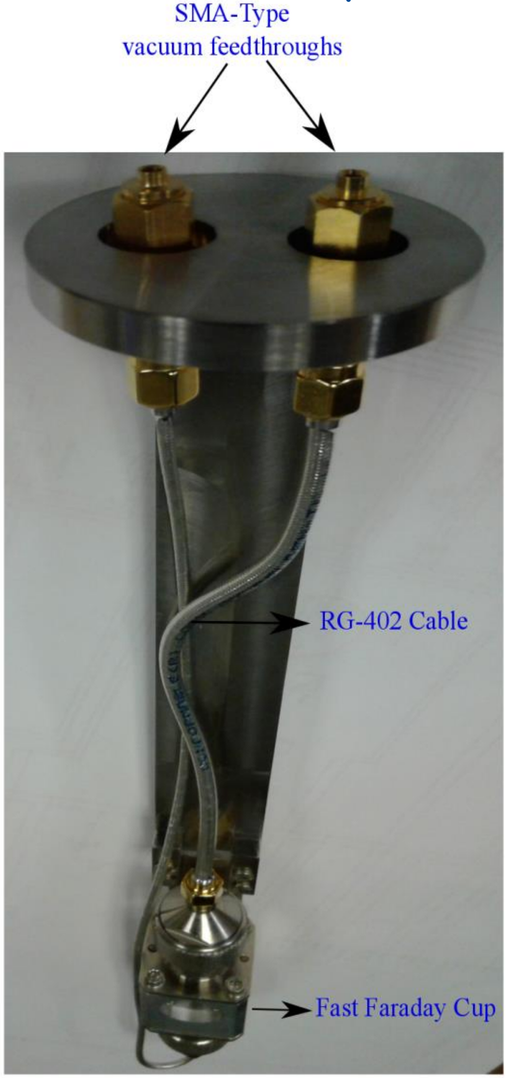
Fast Faraday Cup / Assembly

- Two N-type connectors are mounted concentrically each side of the FFC head
- The head is connected in vacuum to two SMA-type vacuum feedthroughs using RG-402 cables.
- The head is moved in the vertical direction by a stepping motor.

FFC Head

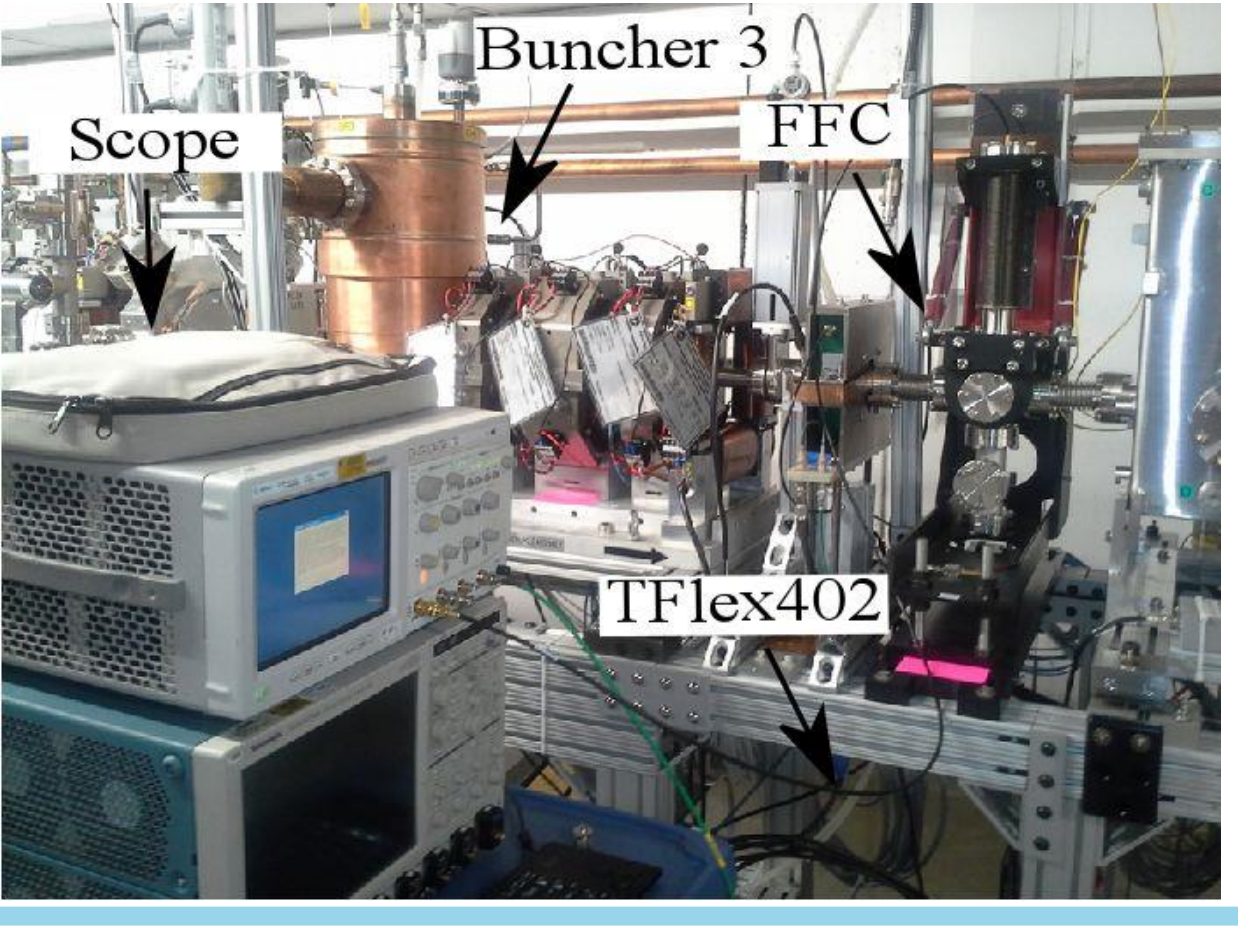


FFC Assembly



Fast Faraday Cup / Scope Connection inside the cave

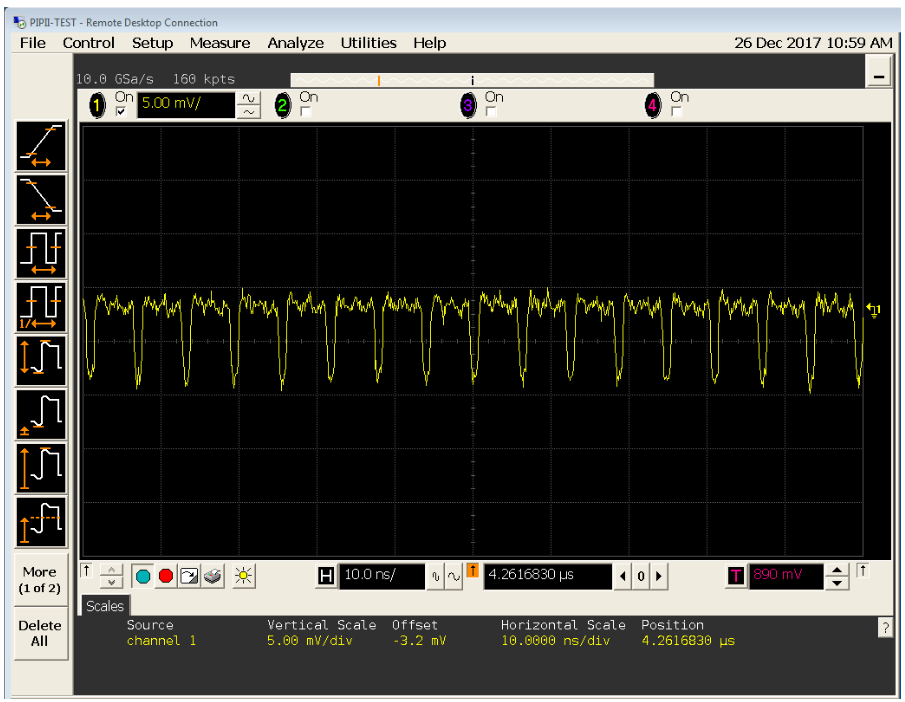
- One of the SMA vacuum feedthroughs is terminated by a 50 Ohm load, and another one is connected by a 3-feet TFlex-402 cable to a fast scope (6 GHz Bandwidth Agilent Infiniium)
- The scope is remotely operated from the control room



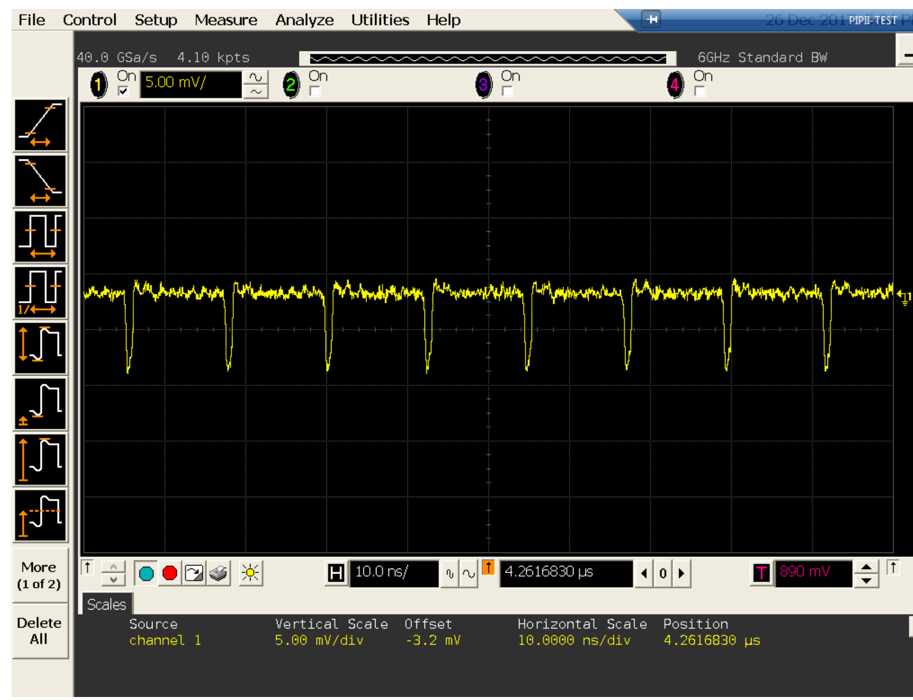
Fast Faraday Cup / Signal Kickers Off and Kickers On (5mA)

- The FFC requires a precise alignment with the beam. Once an optimized signal is obtained, data are saved directly in the shift folder in the format of an excel file of about 100 kb.
- We operate the FFC with short pulses (10 μs) and at a repetition rate of 1 Hz.

Kickers Off

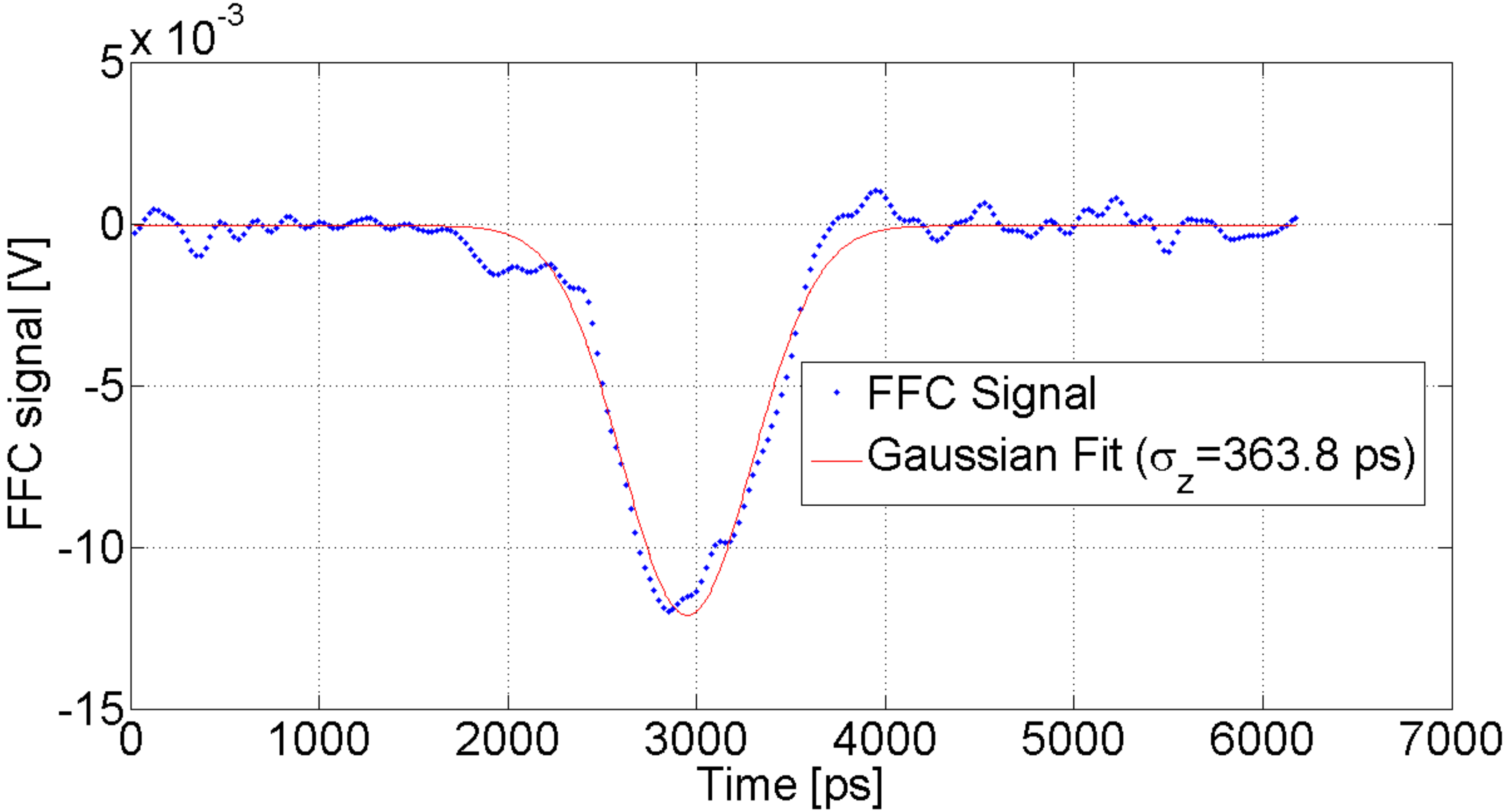


Kickers on



Gaussian Fit of the signal from the FFC and estimate of the corresponding RMS bunch length. (Below 9.3 mA pulse)

- A simple Matlab macro read the FFC raw excel data file and computes for 10 consecutive bunches (5 consecutive bunches if both kickers are tuned on) the RMS bunch length in pico-second by performing a Gaussian fit of the data.



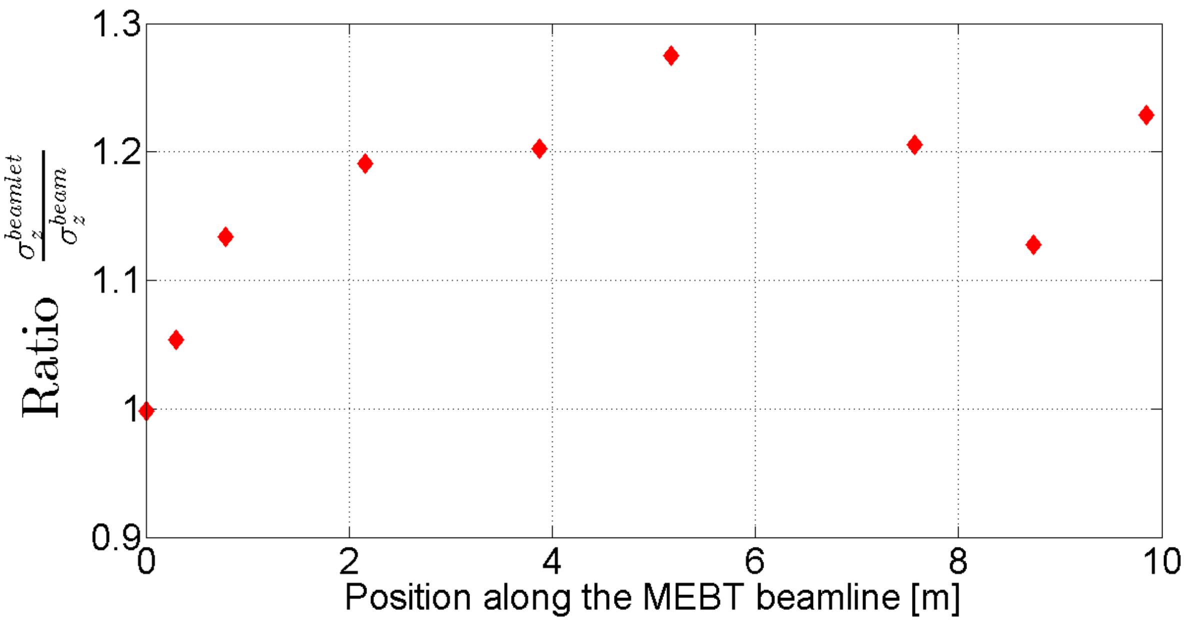
Part IV

Transverse-to-Longitudinal Correlation: Prediction Vs Observation

Beamlet RMS Bunch Length Vs Full Beam RMS Bunch Length
Tracewin predictions starting with a 6D Gaussian distribution at MEBT

- The FFC samples a portion of the beam (about 3% to 5%) with an aperture of 0.8 mm diameter. Tracewin predicts that the beamlet RMS bunch length is *not necessarily* representative of the bunch length of the full beam.

- The plot below shows the ratio of the RMS Bunch Length of the beamlet to the RMS bunch length of the full beam with a 6D Gaussian distribution propagating along the MEBT at 5mA. The beamlet overestimates the RMS bunch length of the full beam by 20% at the end of the beamline.



Beamlet RMS Bunch Length Vs Full Beam RMS Bunch Length

Tracewin predictions starting with the 99.9% RFQ distribution

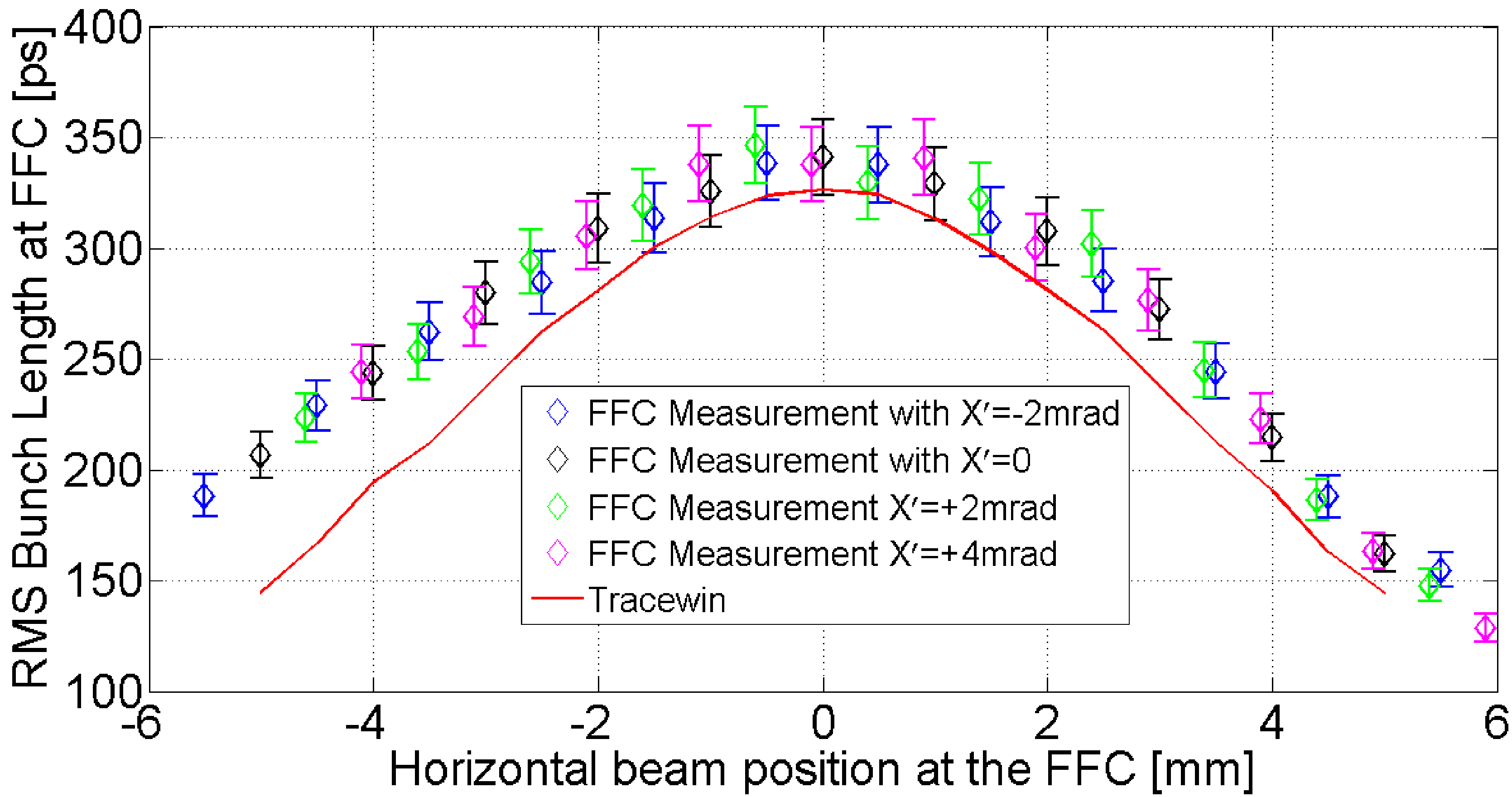
- At 5 mA with the 99.9% RFQ output distribution, TRACEWIN predicts that sampling the RMS bunch length of the beamlet is about 24% larger than the RMS bunch length of the full beam at the end of the MEBT. The effect is space charge related and proportional to the beam current.

Table: Ratio of the Beamlet RMS Bunch Length to Full Beam RMS Bunch Length at 5mA along the MEBT. From Tracewin.

	Tracewin RMS Bunch Length at 5 mA [ps]		
	Beamlet (0.8 mm diameter)	Full Beam	Ratio Beamlet/Full Beam
RFQ Exit	138 ps	129 ps	1.07
MEBT at z=7.83 m	285 ps	243 ps	1.17
MEBT at z=10.15 m	332 ps	267 ps	1.24

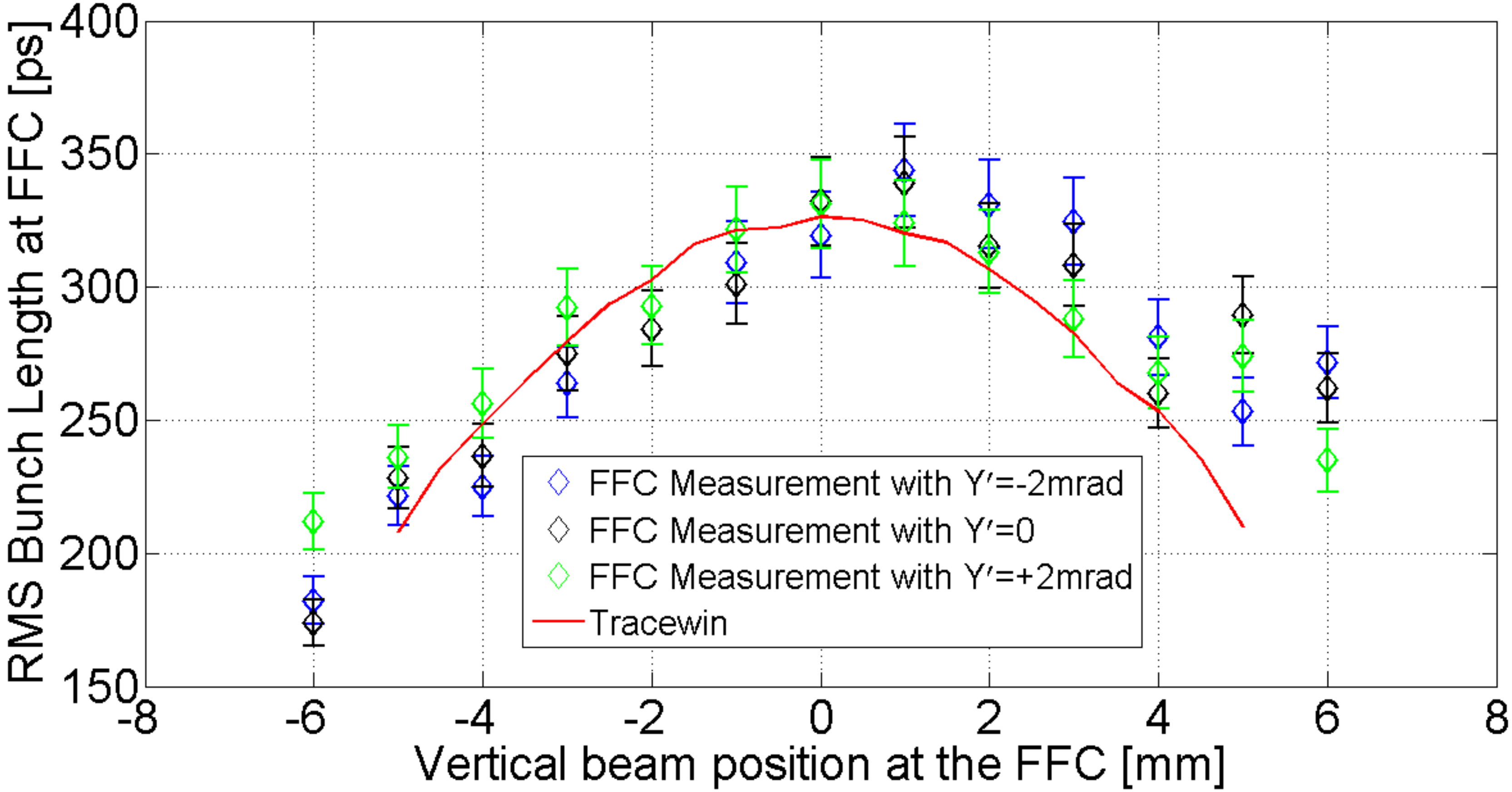
Measurement of the RMS bunch length across the beam
Horizontal scan at 5mA

- As shown in the plot below we did measure a transverse-to-longitudinal correlation. The RMS bunch length in the core of the beam is larger than on its edge, as predicted by Tracewin.



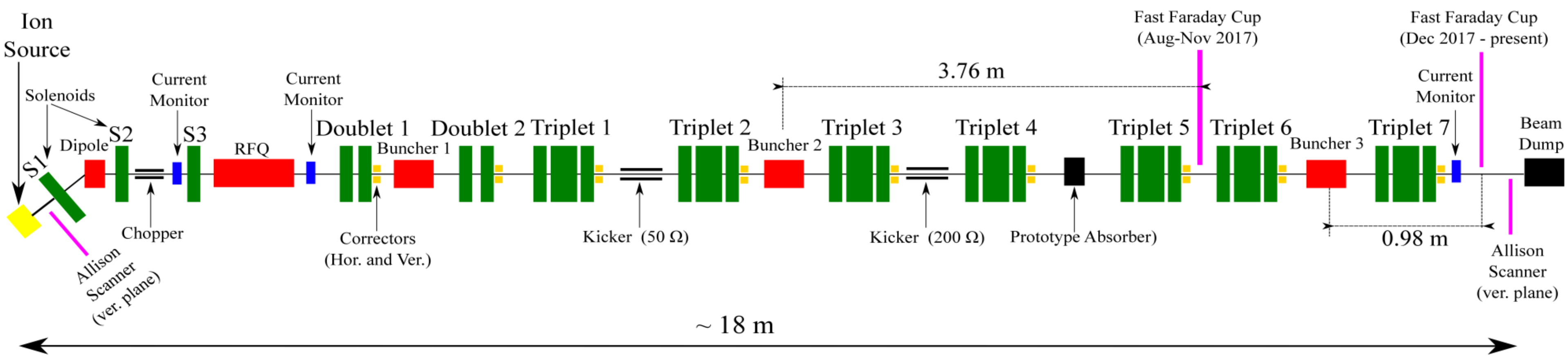
Measurement of the RMS bunch length across the beam
Vertical scan at 5mA

- The same transverse-to-longitudinal correlation was observed in the vertical plane at the same location and under the same beamline condition.



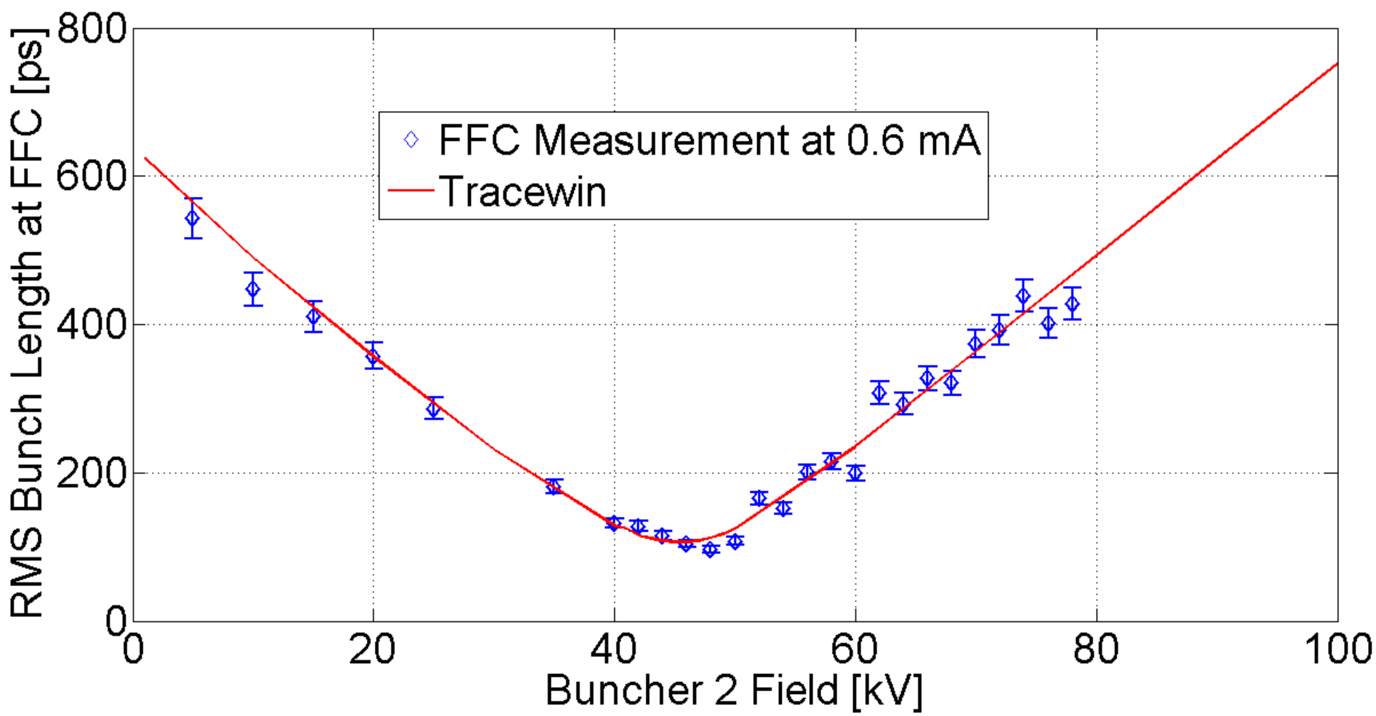
Part V

Longitudinal Emittance Estimate at 0.6 mA, 5 mA and 10 mA.



Longitudinal emittance estimate at 0.6 mA (Pencil Beam)
FFC Bunch Length Measurement Vs Buncher 2 Field

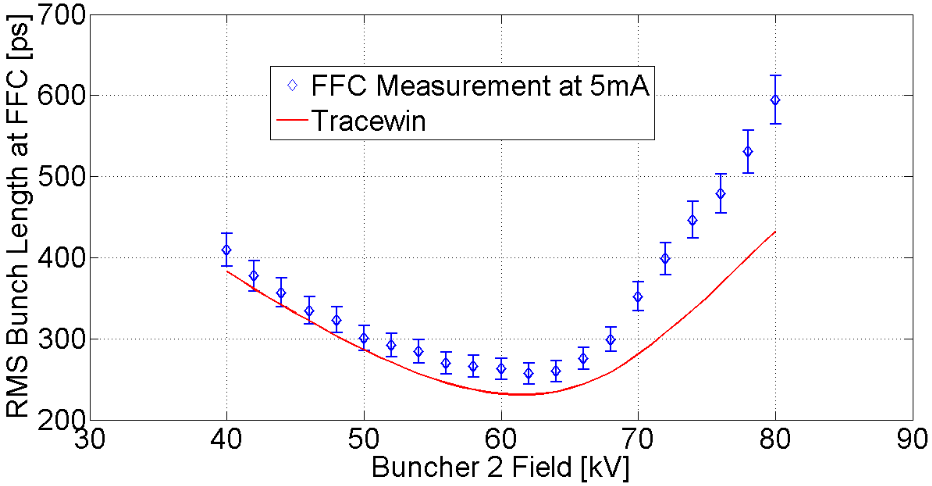
- Measurements of the RMS bunch length for different Buncher 2 Field with the FFC located downstream of Buncher 2 have been performed for 0.6 mA.
- Taking the 99.9% distribution obtained from Tracewin at the RFQ exit and propagating this distribution up to the location of the FFC downstream of Buncher 2 shows a good agreement with the simulation (taking a 0.8 mm aperture in TRACEWIN at the location of the FFC to sample the core of the beam)



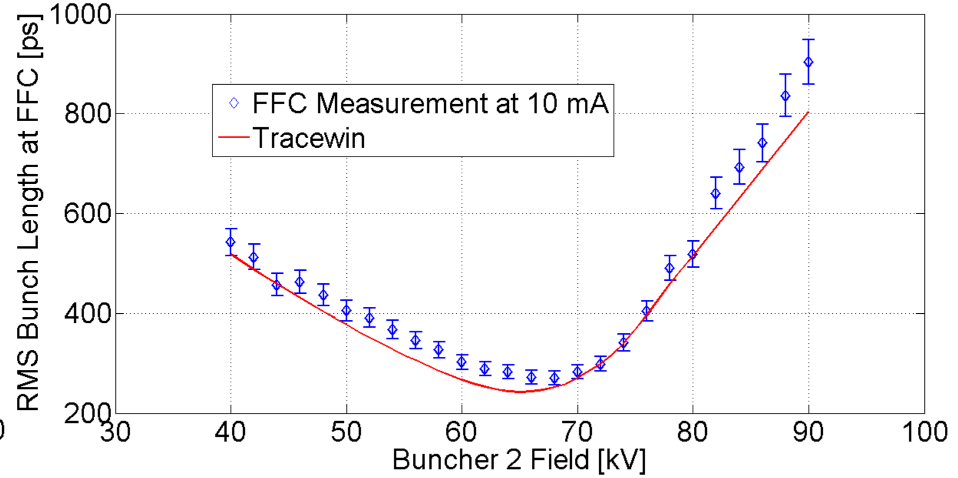
Longitudinal emittance estimate at 5 mA and 10 mA
FFC Bunch Length Measurement Vs Buncher 2 Field

- The same measurements were performed at 5mA and 10mA.
- Simulations with TRACEWIN show for both cases a reasonable agreement taking the 99.9% distribution with 0.26 mm-mrad of long. emittance.
- The longitudinal emittance at the RFQ exit does not seem to vary as a function of the beam current and seems to stay at around 0.26 mm-mrad.

Bunch Length Vs Buncher 2 Field 5mA



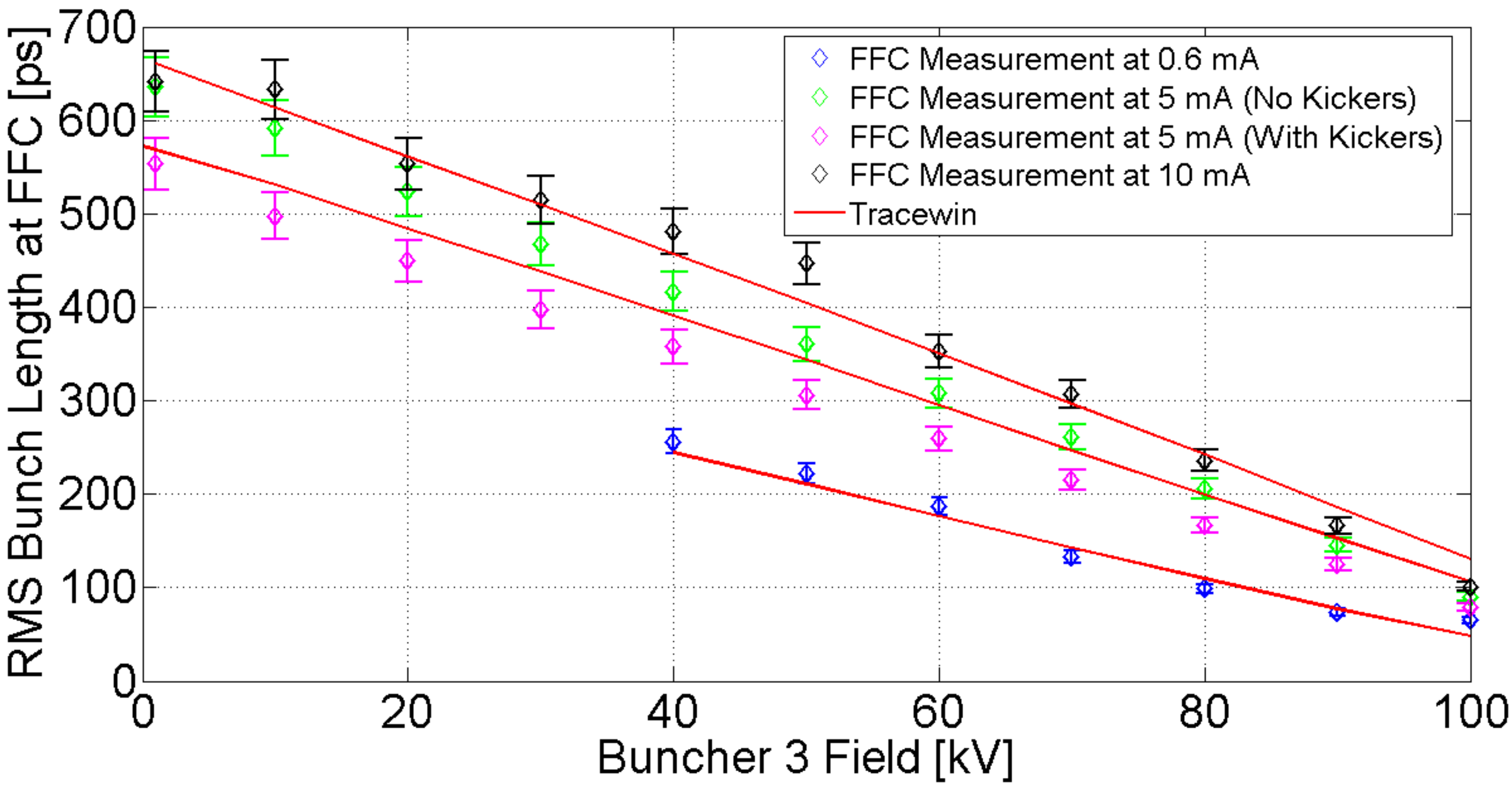
Bunch Length Vs Buncher 2 Field 10 mA



Longitudinal emittance estimate at 0.6 mA, 5mA and 10 mA

FFC Bunch Length Measurement Vs Buncher 3 Field

- Agreement with Tracewin is excellent traking the 99.9% distribution for which the longitudinal emittance is 0.26 mm-mrad.



Summary

- Start-to-end simulations are critically important in order to properly describe the transverse-to-longitudinal correlation occurring in the beam.

- The transverse-to-longitudinal correlation increases as a function of beam current and position.

- The actual start-to-end model of the PIP2IT injector properly reproduce the RMS bunch length measured with the FFC, from low current (0.6mA) to large current (10mA). The RMS longitudinal emittance is estimated at 0.26 mm-mrad from 0.6 mA to 10 mA

Acknowledgements

- Participation in measurements: B. Hanna, L. Prost, A. Saini, A. Shemyakin,
- FFC head (idea, RF and mechanical design, assembling): D. Sun
- Proposal to use FFC and its first versions, organization of instrumentation part: V. Scarpine
- FFC assembly mechanical design: B. Hartsell
- Setting up the scope: B. Fellenz, D. Frolov, D. Slimmer
- MWS Model of the dipole: G. Romanov
- TRACK/TRACEWIN support: B. Mustapha (ANL), D. Uriot (Saclay)
- Thanks to the entire PIP2IT team for making the machine work